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Eccentric knee flexor strength and between limb strength asymmetries in cricket

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Eccentric Knee Flexor Strength and Between Limb Strength Asymmetries in Cricket

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Research

Abstract

Cricket was once regarded as a “moderate injury risk” sport. However, more recent research suggests that the injury rate in elite cricket is rising, with hamstring strain injuries (HSIs) one of the most common and severe injuries (Frost and Chalmers, 2014). Multiple cricket playing nations have documented the occurrence of cricket injuries over several seasons and all have demonstrated an increase in injuries over recent times with the introduction of Twenty20 cricket and the increase in matches played per year (Frost and Chalmers, 2014, Orchard et al., 2011). International cricket injury reports suggest that elite pace bowlers are the most at risk of incurring an injury throughout each season, with a high affiliation to HSIs (Frost and Chalmers, 2014, Mansingh et al., 2006, Orchard et al., 2002, Orchard et al., 2011, Orchard et al., 2006, Stretch, 2003).

Preventative measures can be further deduced from the causation of hamstring strains in order to reduce the risk of sustaining a HSI. Addressing strength imbalances and improving eccentric knee flexor strength have been proposed as a key component of HSI prevention for a variety of high intensity sports. The addition of the Nordic hamstring exercise (NHE) to training programs for elite sports has resulted in significant reductions in HSI rates (Arnason et al., 2008, Askling et al., 2003, Brooks et al., 2006). However, as a HSI may result in chronic inhibition of the injured (weaker) hamstring (Fyfe et al., 2013, Sole et al., 2012), further research needs to be conducted to determine how best to improve recruitment patterns in the injured hamstring. One such approach may be the use of psychological strategies such as augmented feedback (AF). AF has demonstrated improvements in overall quality of training and increases in acute and chronic strength gains, power and skill based tasks when associated with complex movements related to sport (Argus et al., 2011, Jung and Hallbeck, 2007, Kim and Kramer, 1997, McNair et al., 1996, Tod et al., 2005). Considering the importance of increased eccentric knee flexor strength and reduce bilateral limb asymmetries in helping lower the risk of sustaining a HSI, the use of AF during training may provide acute increases in performance during the NHE that result in increased chronic adaptations.

The objective of research study one of this thesis was to compare eccentric knee flexor strength and bilateral asymmetries in elite, sub-elite and school level cricket players; and to determine if playing position and limb role influenced these eccentric knee flexor strength indices. Seventy four male cricket players of three distinct skill levels (elite, sub-elite and school level) performed three repetitions of the NHE on the experimental device. Strength was assessed as the absolute and relative mean peak force output for both limbs, with bilateral asymmetries defined as the percent difference in force between limbs. There were no significant differences between elite, sub-elite and school level athletes for mean peak force (elite $313 \pm 67\text{N}$ and $3.65 \pm 0.89\text{N.kg}^{-1}$; sub-elite $308 \pm 77\text{N}$ and $3.74 \pm 0.96\text{N.kg}^{-1}$;

school $285 \pm 68\text{N}$ and $4.11 \pm 0.77\text{N.kg}^{-1}$ for absolute and relative mean peak force respectively; $P>0.05$) and bilateral asymmetries (elite $11.5 \pm 8.6\%$; sub-elite $15.1 \pm 12.2\%$; school $12.6 \pm 11.6\%$; $P>0.05$) of the knee flexors. There were no significant differences observed between bowlers' and batters' mean peak force ($297 \pm 77\text{N}$ and $3.74 \pm 0.97\text{N.kg}^{-1}$; $305 \pm 65\text{N}$ and $3.99 \pm 0.76\text{N.kg}^{-1}$ for bowlers and batters respectively; $P>0.05$) and bilateral asymmetries ($13.7 \pm 10.3\%$ and $13.2 \pm 12.5\%$ for bowlers and batters, respectively; $P>0.05$). There were no significant differences between front and back limb mean peak force outputs ($299 \pm 79\text{N}$ and $3.83 \pm 1.03\text{N.kg}^{-1}$; $303 \pm 71\text{N}$ and $3.84 \pm 0.84\text{N.kg}^{-1}$ for absolute and relative mean peak force, respectively; $P>0.05$). Skill level, playing position and limb role appeared to have no significant effect on eccentric knee flexor strength and bilateral asymmetries. Further, bowlers and elite players had the lowest relative eccentric knee flexor mean peak force outputs which may present cause for the increased number of HSIs in these demographics. Future research should seek to determine whether eccentric knee flexor strength thresholds are predictive of HSIs in cricket and if specific eccentric knee flexor strengthening can reduce these injuries.

The objective of research study two was to determine the acute effects of real-time visual AF provided during the NHE in reducing bilateral knee flexor strength asymmetries and increasing bilateral knee flexor strength outputs. Forty four male cricket players of two distinct skill levels (sub-elite and school level) performed two testing sessions of the NHE with and without the aid of visual feedback of force production using a cross over study design. Strength was assessed as the peak force output for both limbs, with bilateral asymmetries defined as the percent difference in force between limbs. Differences in mean peak force outputs and bilateral asymmetry were compared between the two conditions. There was a significant increase in mean peak force production when feedback was provided compared to no feedback (NFB) ($d = 0.61$; $P<0.05$), but no significant difference in bilateral limb asymmetry for feedback ($12.7 \pm 12\%$) or NFB ($15.5 \pm 13.2\%$) ($d = 0.41$; $P>0.05$). Increases in force production for the feedback condition were a result of increased force contribution for the weaker limb ($284 \pm 65\text{N}$ vs $299 \pm 72\text{N}$; $d = 0.22$) compared to the strong limb ($327 \pm 77\text{N}$ vs $331 \pm 78\text{N}$; $d = 0.05$). In conclusion, the use of real-time visual feedback during the NHE resulted in significantly increased eccentric knee flexor force. As the significant improvement in the knee flexor force was observed primarily in the weaker limb, the chronic performance of NHE with feedback may reduce HSI risk by increasing eccentric knee flexor strength, especially of the weaker limb.

In summary, the present thesis provides insight into the eccentric knee flexor strength performance characteristics associated with cricket at multiple skill levels and has provided additional training recommendations to a sport that has limited literature encompassing all playing positions. Elite level athlete's absolute eccentric knee flexor strength was found to be

similar to sub-elite and school level cricket players, even though it should be greater considering the elite players' greater body mass, absolute running workloads and higher number of HSIs. Real-time visual feedback during the NHE may be a valuable tool for increasing the acute force outputs which may accelerate strength gains and reductions of between limb strength asymmetries over the course of a typical training cycle. Future research might determine what eccentric knee flexor strength threshold best predicts HSIs in cricket. Once this is known, strength and conditioning staff may focus on their weaker players reaching this threshold, and once that is achieved, direct more focus to reducing between limb strength asymmetries.

Declaration

This thesis is submitted to Bond University in fulfilment of the requirements of the degree of Masters by Research. This thesis represents my own original work towards this research degree and contains no material which has been previously submitted for a degree or diploma at this University or any other institution, except where due acknowledgement is made.

Wade Chalker

Sign: _____

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List of Publications

1. **Chalker, W. J.**, Shield, A. J., Opar, D. A., Keogh, J. W.L. 2016. Comparisons of Eccentric Knee Flexor Strength and Asymmetries Across Elite, Sub-Elite and School Level Cricket Players. *PeerJ*, 4, e1594.
2. **Chalker, W. J.**, Shield, A. J., Opar, D. A., Rathbone, E. N., Keogh, J. W.L. Effect of Acute Augmented Feedback on Bilateral Limb Asymmetries and Eccentric Knee Flexor Strength During the Nordic Hamstring Exercise. *Currently under peer-review in the Journal of Orthopaedic & Sports Physical Therapy*.

List of Conference Proceedings

Chalker, W. J., Shield, A. J., Opar, D. A., Keogh, J. W.L. Eccentric Knee Flexor Strength Asymmetries and the Effect of Augmented Feedback in Elite Cricket Players: A Pilot Study. 5th World Congress of Science and Medicine in Cricket, March 2015, Sydney (Oral Presentation and Abstract) (Appendix E)

Chalker, W. J., Shield, A. J., Opar, D. A., Keogh, J. W.L. A Review of Hamstring Strain Injuries in Cricket and Potential Methods to Reduce the High Occurrence of Strains. 5th World Congress of Science and Medicine in Cricket, March 2015, Sydney (Oral Presentation and Abstract) (Appendix F)

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Abbreviations

AEs	Athlete exposures
AF	Augmented feedback
ARF	Australian Rule Football
BF	Bicep femoris
FB1	Received feedback in the first testing session
FB2	Received feedback in the second testing session
H : Q	Hamstring to quadriceps strength imbalance ratio
H : Q_{conv}	Concentric strength imbalance ratio of hamstrings and quadriceps
H : Q_{func}	Concentric strength of the quadriceps to eccentric strength of the hamstrings ratio
HSI	Hamstring strain injury
IPL	Indian Premier League
NFB	No feedback
NHE	Nordic hamstring exercise
sEMG	Surface electromyography
SM	Semimembranosus
ST	Semitendinosus
T20	Twenty20

Units of Measurement

%	Percentage
<	Less than
>	Greater than
±	Plus or Minus
≥	Equal to or greater than
cm	Centimetres
d	Cohen d effect size
Hz	Hertz
kg	Kilograms
N	Newtons
N.kg⁻¹	Newtons per kilogram
SD	Standard deviation

Chapter One: Introduction

Cricket is a team sport played throughout the world, involving a bat and ball and is played outdoors on a grass field. The game is played between two teams of eleven players, with one team fielding and one team batting until the change of innings. Cricket has several playing positions; batters, bowlers, fielders and wicket keepers. The recognised batters' primary role is to score as many runs as possible; whereas the bowlers' primary role is to dismiss the batters and to restrict the number of runs they score. The wicket-keeper's primary role is to assist the bowlers in dismissing the opposition batters (via catches, stumpings and runouts) and to ensure the remainder of the fielders apply pressure to the batters so to assist in their dismissal (via catches and runouts) in order to restrict the runs scored. Wicket-keepers and bowlers also have a secondary role in supporting batsmen score as many runs as possible.

Cricket involves the use of overhead bowling actions with straight arms and the ball generally bouncing before it is played at by the batter. Cricket has four distinct game formats – test matches on an international level, Shield and First Class matches for domestic competitions, one day matches for international and domestic competitions and Twenty20 (T20) for international and domestic competitions.

The most recent Cricket Australia injury report has identified thigh and hamstring strains as the most commonly occurring injury in first class cricket, a trend that has been observed over a ten year period with the highest injury rate amongst pace bowlers (Orchard et al., 2011). It has been suggested that the introduction of T20 cricket has increased the risk of injuries due to the fast paced nature of the game, decreased rest periods between matches and greater accumulation of high intensity training and competition workloads (Frost and Chalmers, 2014, Orchard et al., 2011, Stretch, 2003).

Hamstring strain injuries (HSIs) are one of the most frequent injuries in elite cricket, accounting for between 8-11.1% of all injuries (Frost and Chalmers, 2014, Orchard et al., 2011). Less injuries are reported for junior cricket, with significantly fewer HSIs compared to elite cricket (Finch et al., 2010). Little is known as to what predisposes cricket players to HSIs but other sporting models suggest common risk factors to include; hamstring muscle weakness or asymmetry, increased age, previous hamstring injuries, lack of hamstring flexibility and muscle fatigue (Brooks et al., 2006, Croisier et al., 2002, Croisier et al., 2008, Gabbe et al., 2006a, Jonhagen et al., 1994, Opar et al., 2012, Orchard et al., 1997, Verrall et al., 2001). Strength imbalances between hamstring muscle groups and limbs have been suggested to lead to HSIs (Opar, Williams, & Shield, 2012) and may be an issue in cricket, especially for pace bowlers who place more stress on their front leg during the bowling phase.

It is important to remember that any form of injury results in time away from training and playing, meaning that elite level teams are paying for an athlete's rehabilitation for an injury that may have been prevented by monitoring early warning signs and implementing new prevention protocols. Not only does player performance decrease after returning from injury (Verrall et al., 2006), but the average cost for a single HSI in 2012 for the Australian Football League was calculated to be \$40,021 per incident (Hickey et al., 2013). While there is no data on cost per HSI in cricket, this is a significant cost per injury for each club that might be reduced with more knowledge on why and how HSIs occurs.

HSIs have remained a common injury site in cricket as well as other sports such as rugby union, soccer and Australian football, suggesting that greater understanding of the causation of hamstring strains is required (Braham et al., 2004, Brooks et al., 2006, Cross et al., 2010, Houghton et al., 2011, Hrysomallis, 2013, Opar et al., 2012, Orchard et al., 2011, Orchard et al., 2010).

Preventative measures can then be further deduced from the causation of hamstring strains in order to reduce the risk of sustaining a hamstring strain. Addressing strength imbalances and improving eccentric knee flexor strength have been proposed as a key component of HSI prevention. The Nordic hamstring exercise (NHE), a body weight eccentric resistance exercise, could provide cricket players a feasible and effective way to reduce the risk of sustaining a HSI. Opar et al. (2013a) have recently developed and validated a hamstring field testing device for the assessment of eccentric knee flexor strength and between limb strength asymmetries via the completion of a NHE. The NHE assessment tool has recently been used to extrapolate risk factor ratios for Australian football players (Opar et al., 2015a) and rugby union players (Bourne et al., 2015b) based on eccentric knee flexor strength and eccentric knee flexor strength asymmetries.

Psychological strategies such as augmented feedback (AF) have demonstrated improvements in overall quality of training as well as reporting increases in acute and chronic strength gains, power and skill based tasks when associated with complex movements related to sport (Argus et al., 2011, Jung and Hallbeck, 2007, Kim and Kramer, 1997, McNair et al., 1996, Tod et al., 2005). Considering the importance of increased eccentric knee flexor strength and reduced bilateral limb asymmetries in helping to lower the risk of sustaining a HSI, the use of AF may provide acute increases in performance during the NHE that may then produce greater chronic adaptations in hamstring strength. It is unknown whether the use of feedback during the NHE may produce acute and/or chronic increases in strength and reductions in between limb strength asymmetries.

This thesis has examined the effect of the change in cricket demands associated with different skill levels on the occurrence of HSI related risk factors, causative factors that lead to hamstring strains, preventative measures that can be implemented to reduce the risk of

hamstring strains, the effect of decreased neural drive following a hamstring strain and the effect of AF to aid performance increases. These topics will help to better understand the requirements of cricket players and what impact HSIs have in sport and how they can be prevented with further research.

Throughout this paper, the term “knee flexors” refer to the muscle action required to produce knee flexion resulting from the involvement of the hamstrings (bicep femoris long head and short, semitendinosus and semimembranosus) muscles assisted by the gastrocnemius. When “hamstrings” is used in the manuscript, it is generally used anatomically in relation to the three muscles i.e., the bicep femoris, semitendinosus or semimembranosus.

Project Aims

Therefore, using the device developed by Opar et al. (2013a), the primary aims of the present project were to:

1. Determine the effect of experience level in cricket and playing position on the extent of bilateral knee flexor strength and between limb knee flexor strength asymmetries through the NHE assessment tool.
2. Determine the effect of AF on between limb knee flexor strength asymmetries and bilateral knee flexor strength outputs during the performance of the NHE.

It was hypothesised that;

1. Elite level cricket players will present with greater eccentric knee flexor strength and reduced bilateral knee flexor strength asymmetries compared to sub-elite and school level cricket players; with bowlers presenting with the greatest limb asymmetry and the front leg being the stronger limb for all playing positions.
2. Real-time visual feedback during the NHE will reduce between limb knee flexor strength asymmetries and increase knee flexor strength outputs.

In order to complete this study, cricket players of three distinct skill levels were recruited from elite, sub-elite and school level competitions. All players had at least two years of experience with playing at their skill level. All data was collected at the start of each team’s pre-season training to control for any potential between group variations in training loads, as used in previous NHE studies involving comparisons of different playing groups (Bourne et al., 2015b, Opar et al., 2015a).

Chapter Two: Literature Review

Literature Search

The literature reviewed in this thesis was sourced using SPORTDiscus and Pubmed databases. Key words used during the search included; cricket, hamstrings, strains, injuries, prevention and Nordic hamstring exercises. Articles were searched within a date of 1969-July, 2015, obtaining full text articles. Articles that matched key words in the abstract were included for review. Further articles were sourced after review of article reference lists if the articles were relevant to key words. From the abstract review, articles were included if they related to cricket injuries, hamstring strains, causation, treatment or prevention.

Evolution of Cricket

Cricket has developed significantly over the years, with much controversy over the origins of the game. The original game of cricket was played over 5 days between two teams with unlimited overs (six balls bowled per individual bowler before the bowler has to change) and is still played today in the form of test cricket between international sides (Cannonier et al., 2013). Domestic first class cricket in Australia adopts a similar game type that is played across 4 days between two teams and is currently referred to as Sheffield Shield cricket. In the 1960s the introduction of limited overs (50 overs) cricket was largely welcomed as it began to draw in larger crowds as the match was completed in one day (Cannonier et al., 2013). Today, one day cricket is played by all Australian domestic first class teams as well as on an international level. Limited overs cricket was played between Australia and England in 1971 in the first ever One Day International, shortly followed by a cricket world cup between multiple countries in 1975 (Cannonier et al., 2013).

More than 40 years after the introduction of one day cricket, a new concept, T20 cricket was developed in 2003, consisting of 20 overs per side, it provided an even shorter, more intense, action packed game targeted at increasing spectator numbers and interest (Cannonier et al., 2013, Rumford, 2011). Australia was quick to adapt the new T20 concept with the first domestic T20 competition beginning in 2005 (Orchard et al., 2011). The development of T20 cricket has resulted in drastic changes to a player's workload during a competitive season with increased matches played per year and greater relative running distances (meters per hour) observed during T20 cricket compared to one day and multi day cricket (Petersen et al., 2010). Elite level cricket players involved in domestic cricket and international representation have an increasing number of chances to play more cricket each year through international test matches, shield matches, one day matches and T20 matches. However, each of these forms of cricket may place somewhat different demands on the body and contribute to an increase in players' workloads and injury risk.

Following the increasing interest in T20 cricket, the T20 cricket world cup was hosted in 2007 which gave rise to an Indian Premier League (IPL) for cricket, a two month competition where competitors were able to receive multi-million dollar contracts (Cannonier et al., 2013). The formation of the IPL increased the incentive for players to play more than just their domestic cricket season. The top teams involved in the Australian T20 competition have the opportunity to play in a Champions League competition which sees the best T20 teams in the world go head to head, once again increasing the opportunity for cricket players to expose themselves to multiple formats of the game and multiple career opportunities (Orchard et al., 2011).

Elite cricket players have the ability to earn more money through wider career opportunities available through multiple cricket formats and competitions. The IPL has increased player's interest to do well and expose themselves to more aspects of the game to gain recognition that can result in well paid contracts (Cannonier et al., 2013, Rumford, 2011). The introduction of shorter games has increased the crowd attendance at matches and viewing numbers of matches which has helped gain a greater appreciation for the sport around the world (Cannonier et al., 2013, Rumford, 2011). Therefore, the evolution of cricket has been viewed as generally positive for the sport, but it has also had some negative impacts.

Increased Demands of Cricket

Elite sports people are continually expected to perform at higher levels for longer seasons than has been required in previous years. Therefore, elite players are required to commit to longer and harder training sessions in order to consistently excel in their chosen sport, with the modern cricketer being no exception to this training expectation (Stretch, 2003). The introduction of multiple cricket formats for players to continually excel has resulted in an increase in player workloads and matches played per year. A sport that was once regarded as "moderate injury risk" in the 1970s, cricket now results in an increase in player injuries as the repetitive nature of the sport and increased expectation to perform burdens the players (Stretch, 2001, Stretch, 2003).

Cricket players are increasingly exposing themselves to different formats of the game to advance their career and earning potential. The resulting factor of this exposure means a decrease in rest periods and an increase in playing and/or training hours. Orchard et al. (2011), calculated that over a ten year period in Australian cricket, the median days between Sheffield shield matches dropped from 16 days in the 2001-2002 season to 6.5 days in the 2010-2011 season. The decreased days between shield matches is associated with scheduling problems caused by the introduction of T20 cricket which is played over what used to be a season break for the players over Christmas (Cannonier et al., 2013, Orchard

et al., 2011). During the off-season for domestic Australian cricket, international players are exposed to further match scheduling in international competitions which decreases the total period for these players to rest between matches and seasons.

Workloads faced by cricket players are continuing to increase each year, with Orchard et al. (2011) reporting the total number of overs bowled each year in domestic cricket increased from 15,891 in the 2001-2002 season, peaking to 17,341 overs in the 2009-2010 season. The introduction of T20 cricket has played a role in the increased number of overs bowled. All of these factors appear to be associated with an increase in injuries for cricket players in domestic and international cricket. The reported injury prevalence is higher in England than in Australia, perhaps a result of the even greater number of scheduled matches for first class players in England (Leary and White, 2000, Orchard et al., 2006). New Zealand cricket has demonstrated a similar increase in injury prevalence rates from 9.5% in 2002-2003 to 15.4% in the 2007-2008 season over a six year period, corresponding with the associated format changes to the game (Frost and Chalmers, 2014).

Cricket is constantly evolving and the demands on cricket players are continuing to increase, in turn, an increase in player injuries is starting to become a common trend. Among the increase in injuries occurring in cricket, HSIs are continuing to see a similar trend in the rise of the number of incidences occurring each year.

Injuries in Cricket

The interest in cricket injuries across cricket playing nations has developed with the increasing demand and changes of the sport. There is more emphasis on trying to find a cause to cricket injuries each year. Multiple cricket playing nations have documented the occurrence of cricket injuries and all have demonstrated an increase in injuries over recent times with the introduction of T20 cricket and the increase in matches played (Frost and Chalmers, 2014, Orchard et al., 2002, Orchard et al., 2011, Stretch, 2003). Injuries vary across nations but there are some similar findings across the research literature.

It has been recommended that cricket injury studies present data as injury incidence and injury prevalence if exposure time is available, if it is not available then descriptive statistics may be presented (Orchard et al., 2005). Injury incidence presents the results of new injuries or new and recurrent injuries occurring over a given time period, it can be presented as match injury incidence, training injury incidence or seasonal injury incidence rates as each situation is exposed to different times and overs bowled (Orchard et al., 2005). Injury prevalence is expressed as a percentage, representing the percentage of players that are not available for match play on average for that team for the season, with this calculated separately for different types of cricket (One day matches, test matches, etc.) (Orchard et al., 2005). Where possible, injuries are presented as a total percentage of the occurrence of the

injury due to the inconsistencies of injury incidence reporting formats. Across four cricket playing nations that have published injury reports over recent history, Table 1 demonstrates a number of similarities.

Table 1: Cricket injury data from multiple representative teams

Study (year)	Team Country	Study Design	Seasons Covered (Financial Year)	Sample Size	Total Injuries	Average Injuries Per Year	Most Frequently Injury-Affected Playing Position	Most Frequently Injured Body Part	Most Frequently Occurring Injury Type	Match Days Lost
Frost and Chalmers (2014)	New Zealand International and Domestic	Prospective	2002-2003 to 2007-2008	248	415	69	Bowlers (n=202; 48.7%)	Lower limb (n=192; 46.5%)	Hamstring Strains (n=46; 11.1%)	2651
Mansingh et al. (2006)	West Indies – International and Multiple Countries	Prospective	2003-2004	195	50	50	Pace Bowlers & Batsman (40% each)	Phalanges & Lumbar Spine (22% and 20% respectively)	Muscle Strains (26%)	Not Stated
Orchard et al. (2002)	Australia International and Domestic	Retrospective (1995-1998) and Prospective (1998-2001)	1995-1996 to 2000-2001	Not Stated	527	88	Pace Bowlers (14%)	Lower Limb (49.1%)	Hamstring strains, wrist & hand injuries (n=56; 11% each)	Not Stated
Orchard et al. (2011)	Australia International and Domestic	Prospective	2001-2002 to 2010-2011	Not Stated	Not Stated	Not Stated	Pace Bowlers (18.2%)	Not Stated	Hamstring Strains (peaking 2008-09, n=43)	Not Stated
Orchard et al. (2006)	Australia International and Domestic	Retrospective (1995-1998) and Prospective (1998-2005)	1995-1996 to 2004-2005	Not Stated	886	89	Pace Bowlers	Not Stated	Not Stated	Not Stated
Stretch (2003)	South Africa International and Domestic	Retrospective	1998-1999 to 2000-2001	Not Stated	812	271	Bowlers (41.3%)	Lower limb (49.8%)	Hamstring Strains & Tears (n=72; 8.8%)	Not Stated
Leary and White (2000)	England Domestic	Retrospective	1985-1986 to 1994-1995	54	990	99	Bowlers	Lower Limb (44.9%)	Thigh & Calf Strain/Tear (24.6%)	Not Stated

These studies summarised in Table 1 suggest that pace bowlers are the most at risk of incurring an injury throughout each season (Frost and Chalmers, 2014, Mansingh et al., 2006, Orchard et al., 2002, Orchard et al., 2011, Orchard et al., 2006, Stretch, 2003). Most reports suggest that lower limb injuries, in particular HSIs, are the most commonly occurring injury that can affect not only pace bowlers but players while batting and fielding (Frost and Chalmers, 2014, Orchard et al., 2002, Orchard et al., 2011, Orchard et al., 2006, Stretch, 2003). Junior Australian Cricket Players (U12-U16yrs) report a lower overall injury rate compared to sub-elite and elite players with most injuries being associated with ball contact (Finch et al., 2010). There was no one playing position in junior cricket that sustained more injuries throughout the season compared to another playing position (Finch et al., 2010).

Chronic and acute lumbar spine injuries have a greater impact on player performance compared to more common injuries. Although lumbar spine injuries such as stress fractures are not always the most common injury, they result in a greater amount of time lost per injury when compared to other injuries due to their slow recovery rate (Dennis et al., 2005, Frost and Chalmers, 2014, Orchard et al., 2011, Nuttridge and Milburn, 2004). The cause of most pace bowling injuries is often excessive prior workloads, illustrated by the high incidence of pace bowling injuries in first class matches that immediately followed the champions league T20 competition, where there were no injuries in the T20 (Orchard et al., 2011).

It should be noted that some studies lacked a comprehensive evaluation of the results. Studies that did not include the total number of athletes involved in the study do not allow for further understanding of the impact of injuries sustained and therefore, leave it up to interpretation as to how big the impact of the injuries are in the sport (Orchard et al., 2002, Orchard et al., 2011, Orchard et al., 2006, Stretch, 2003). Furthermore, the impact of the sustained injuries can be presented in the match days lost, although there was only one study to publish the number of days lost due to injury (Frost and Chalmers, 2014). Every study presented in Table 1 had injuries reported and examined by medical staff of each team to ensure the correct diagnosis.

There are no recent studies that follow international players that play in multiple T20 competitions to document the rate of injuries that occur in these new formats such as the Champions league and IPL competitions. Further research following high profile cricket players that have an increase in scheduled matches by multiple contracts is needed.

Hamstring Strain Injury Occurrence Rates in Cricket

Amongst the multiple reports of cricket injuries seen in Table 1, HSIs have shown some consistency in being one of the most commonly occurring injury sites. A further breakdown of the literature in Table 2 demonstrates a high occurrence rate of HSIs across different countries and different playing periods with HSIs accounting for 8-11.1% of all injuries in

each playing period. The incidence rates of HSI in cricket are reported differently between studies and are often hard to compare (Appendix D).

Table 2: Hamstring injury occurrences in domestic and international cricket teams over multiple playing seasons

Study (year)	Team Country	Seasons Covered (Financial Year)	Number of Participants	Total Injuries	Hamstring Injuries	% of Total Injuries
Frost and Chalmers (2014)	New Zealand International and Domestic	2002-2003 to 2007-2008	248	415	46	11.1
Mansingh et al. (2006)	West Indies – International and Multiple Countries	2003-2004	195	50	4	8
Orchard et al. (2002)	Australia International and Domestic	1995-1996 to 2000-2001	Not Stated	527	56	10.6
Orchard et al. (2011)	Australia International and Domestic	2001-2002 to 2010-2011	Not Stated	Not Stated	208 (Thigh & Hamstring)	Not Stated
Stretch (2003)	South Africa International and Domestic	1998-1999 to 2000-2001	Not Stated	812	72	8.9

Limited research has examined when HSIs occur during the game of cricket, whether it be at training or in match play as well as who are most susceptible to sustaining a HSI. Hamstring strains occur in all forms of the game, bowling, fielding, batting, training and match play (Orchard et al., 2010). Orchard et al. (2011) have suggested that bowlers are most prone to HSIs and proposed that the risk for HSIs in pace bowlers is greater during the end of the bowling phase for the front leg, as it undergoes high-level eccentric contractions due to the body decelerating over the front leg during delivery of the ball (Figure 1). Strength imbalances between hamstring muscle groups have been suggested to lead to HSIs (Opar et al., 2012) and may be a resulting factor for pace bowlers who place more stress on the front leg during the bowling phase. However, there is limited evidence to support the idea that HSIs occur more in bowlers compared to other playing positions.



Figure 1. The phase of the bowling action where it is believed most HSIs occur to the front leg as it undergoes a large amount of deceleration.

Stretch (2003) used a questionnaire to obtain data from team physiotherapists and doctors regarding information about each injury. These sports medicine professionals reported, that of all the 812 injuries sustained during the study period, the primary mechanism of injury was the delivery and follow through phase during the pace bowling action (25.6%) and overuse (18.3%), with the remainder relating to other factors such as fielding injuries and other minor incidences. The results reported by Stretch (2003), suggest that pace bowlers are the most at risk of injury and hamstring strains may have a high occurrence rate within pace bowlers.

Hamstring Injury Rates in Comparison to Other Sports

The rate of occurrence of hamstring strains in cricket compares favourably with the results from other popular high intensity sports. However, due to inconsistencies between incidence reporting methods, it is hard to accurately compare sports (Appendix D). The nature of cricket results in players performing multiple stop-start actions based on several accounts of high intensity efforts (Houghton et al., 2011). It has been suggested that HSIs are most often associated with sports that involve explosive activities with repeated bouts of sprinting (hamstring injury incidence rates of 0.69/1000 athlete exposures (AEs) for male soccer players, 0.38/1000 AEs for female soccer players and 0.60/1000 AEs for male American football players) (Cross et al., 2010). Over a four year study period, sports that

demonstrated high intensity efforts over a small to large distance range such as soccer and American football often had the highest occurrence of hamstring injuries when compared to other sports such as lacrosse, basketball, baseball, tennis and cross country (Cross et al., 2010).

When compared to Australian Rules Football (ARF), cricket has similar injury patterns in terms of HSIs. In two different studies with 320 and 301 amateur and community level ARF players, hamstring strains accounted for 14% and 7.2% respectively of all injuries over a single season (overall injury incidence rate of 57.4/1000 days of play and 12.1/1000 player hours respectively) (Braham et al., 2004, Gabbe et al., 2002). A review of literature involving injuries in ARF identified muscle strains, in particular, hamstring and groin strains as the most commonly occurring injury in the sport (Hrysomallis, 2013). Similar results have been documented in England rugby union teams, where HSIs account for 6-15% of all injuries and rate amongst the most frequently occurring injury (Brooks et al., 2006). Brooks et al. (2006) reported that HSIs in professional rugby union occurred in 22% of the players ($n = 546$), with a hamstring injury incidence rate of 0.27/1000 player training hours and 5.6/1000 player match hours. That is almost half of what is reported in semi-professional soccer (0.5/1000 player hours) where 13% of all injuries were sustained to the hamstring muscles (Arnason et al., 2004). Comparing the total percentage of hamstring strains occurring in cricket (as summarised in Table 2) and the results produced in ARF, soccer and rugby studies suggests that the rates of hamstring injuries in cricket are substantial as they are in other high intensity sports which often report HSIs as the most commonly occurring injury.

Causation of Hamstring Strains

Due to the limited publications that have used valid approaches to quantify the mechanisms contributing to HSIs involved in cricket, the focus of the present review of the literature is on running as this is most representative of the actions involved in cricket and has research literature containing many high quality studies.

As shown in Figure 2, the hamstring muscles comprise three biarticular muscles; biceps femoris (BF) long head, semitendinosus (ST) and semimembranosus (SM) and one monoarticular muscle; biceps femoris short head, all of which are agonist muscles for knee flexion (Kumazaki et al., 2012, Opar et al., 2012). The biarticular muscles of the hamstrings also produce extension of the thigh at the hip joint with the ability to medially and laterally rotate the thigh and leg (Drake et al., 2010). High incidences of HSIs are associated with forceful repetitive use of the hamstrings during activities such as kicking, sprinting, stopping, accelerating and tackling, suggesting that running activities are likely causes of HSIs (Arnason et al., 2008, Brooks et al., 2006, Ekstrand et al., 2012, Kumazaki et al., 2012, Opar et al., 2012, Orchard, 2001, Verrall et al., 2001, Woods et al., 2004). It has been found that

the BF long head and SM are the most susceptible to muscle strain injuries as they are placed under the greatest amount of stretch during periods of maximal force production (Kumazaki et al., 2012, Opar et al., 2012).

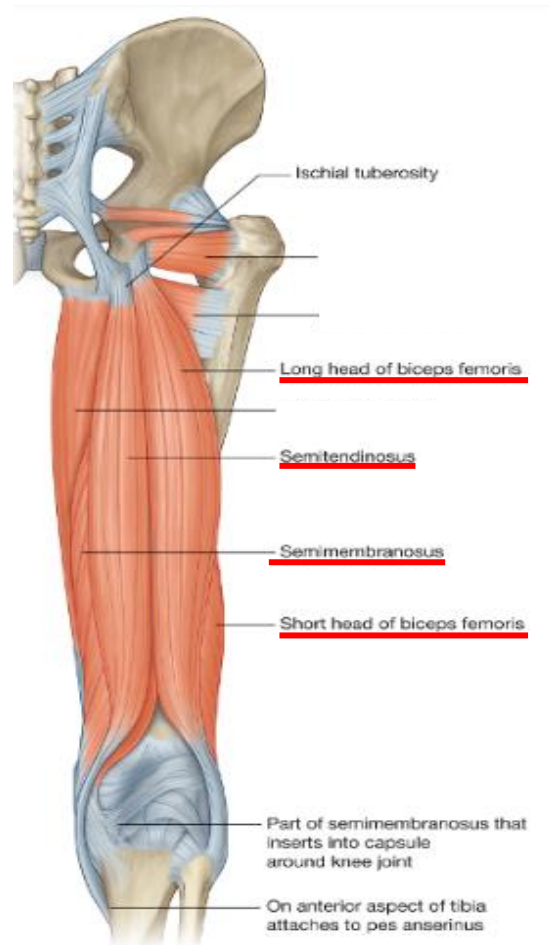


Figure 2: Anatomy of hamstring muscles; Bicep femoris long and short head, Semitendinosus and Semimembranosus have been highlighted. Adapted from Drake et al. (2010)

Biomechanical analyses of an athlete's running gait has identified that the hamstring muscle group undergoes peak activation during the latter stage of the swing phase; in the terminal swing and early stance phase, this period coincides with the greatest amount of muscle lengthening in the hamstrings (Askling et al., 2008, Chumanov et al., 2011, Kumazaki et al., 2012, Opar et al., 2012, Petersen and Hölmich, 2005, Yu et al., 2008, Thelen et al., 2005b, Woods et al., 2004, Chumanov et al., 2007). Figure 3 provides a representation of the muscle activity of selected agonist muscles throughout the different gait phases. The terminal swing phase has often been linked to being the most common time for HSIs to occur as the hamstrings are forcefully contracting eccentrically to decelerate the extending knee whilst being under maximum stretch due to hip flexion and knee extension

associated with this phase (Chumanov et al., 2011, Novacheck, 1998, Opar et al., 2012). The eccentric nature of the movement during the terminal swing phase is considered the most hazardous in terms of sustaining a muscle strain as the movement demands can often exceed the mechanical limits of the tissue (Lee et al., 2009, Opar et al., 2012, Thelen et al., 2005a). This is due to the hamstring muscles being under the greatest amount of stretch during a maximal contraction. It is therefore suggested that eccentric contraction is an essential movement for a HSI to occur based on the lack of strain injuries sustained in concentric contraction biased sports such as cycling and swimming (Heiderscheit et al., 2005, Johnson, 2003, Mellion, 1991, Opar et al., 2012, Schache et al., 2009).

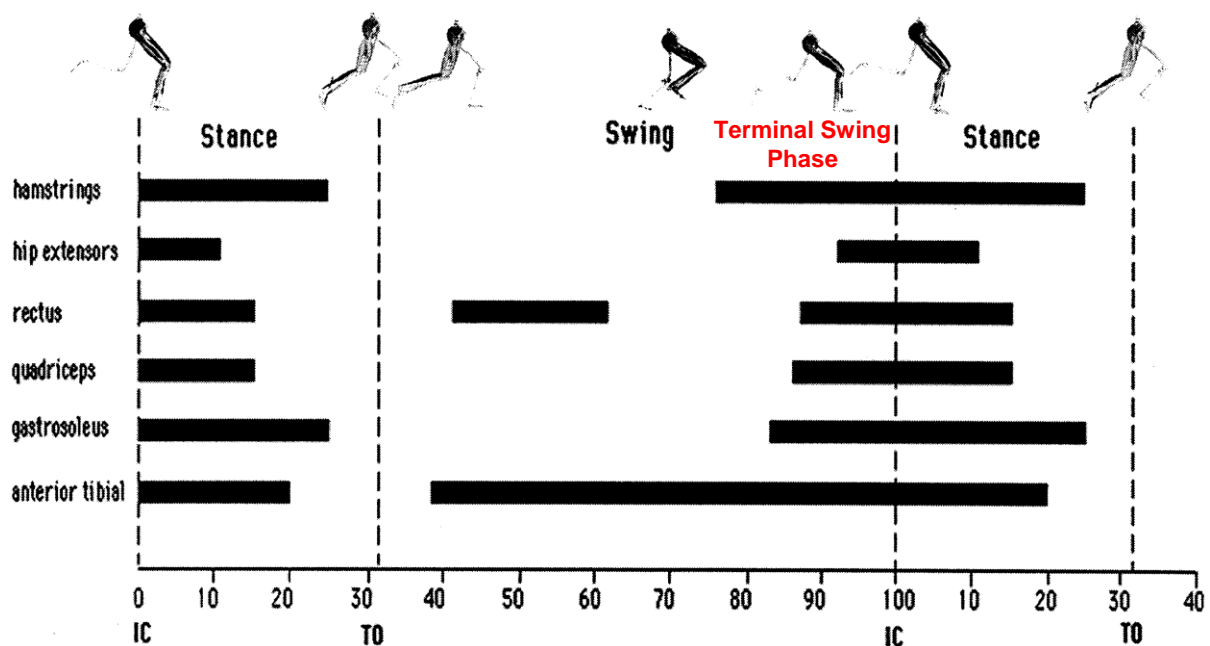


Figure 3: Muscle activity represented by solid bars in relation to the running gait cycle for hamstrings, hip extensors, rectus, quadriceps, gastrosoleus (gastrocnemius and soleus) and anterior tibial muscle groups. Initial contact (IC) and toe off (TO) are represented for the active limb. Adapted from Novacheck (1998).

Another cause of HSIs may occur during the ground contract phase of overground sprinting where hip extension produces maximal concentric torque resulting in increased loading on the hamstrings; this mechanism of injury occurs at a much lower incidence than in the latter part of the swing phase (Chumanov et al., 2011, Yu et al., 2008). There remains uncertainty as to whether HSIs are a result of a single major event that exceeds the mechanical limits of the hamstrings or whether it is a result of accumulated microscopic muscle damage, however, both may be contributing factors to HSIs (Opar et al., 2012). During running events, high levels of eccentric force encountered by the hamstring muscles as well as the physical stress placed on the muscle, incorporated with a major event or

accumulated microscopic damage to the muscle are considered major factors that increase the risk for HSIs.

Risk Factors Leading to Hamstring Strains

Given the high incidence rate of HSIs in different sports across multiple countries, risk factors that lead to HSIs have been extensively studied, with many factors identified. Risk factors that have been associated with HSIs are; hamstring muscle weakness, increasing age, previous hamstring injury, lack of hamstring flexibility, poor lumbar posture, muscle fatigue and biomechanical abnormalities (Bennell et al., 1998, Brooks et al., 2006, Copland et al., 2009, Croisier et al., 2002, Croisier et al., 2008, Ekstrand et al., 2012, Gabbe et al., 2002, Gabbe et al., 2006a, Heiser et al., 1984, Jonhagen et al., 1994, Opar et al., 2012, Orchard et al., 1997, Orchard, 2001, Sugiyama et al., 2008, Verrall et al., 2001, Woods et al., 2004). Risk factors can be broken down to modifiable risk factors and non-modifiable risk factors for HSIs.

Non-Modifiable Risk Factors

Age

Increasing age has long been suggested as a risk factor for HSIs. A number of studies have investigated the effect of age on the cause of HSIs showing a significant increase in risk with an increase in age for Australian football players and soccer players suggesting that players over the age 24 are at greater risk of sustaining a HSI (Gabbe et al., 2006a, Opar et al., 2012, Verrall et al., 2001, Woods et al., 2004, Orchard, 2001). The risk associated with increasing age has been evaluated independently of other risk factors associated with HSIs such as previous injury (Gabbe et al., 2006a, Verrall et al., 2001, Woods et al., 2004). Although multiple studies have reported that age increases the risk of HSIs, there is no convincing explanation as to why older athletes are more susceptible, as in all cases, the athletes are training regularly with no differences in hamstring strength or performance fitness compared to younger athletes (Opar et al., 2012, Verrall et al., 2001). It may be possible that with an increase in age, athletes have accumulated greater degrees of micro-trauma which results in the older athletes having a greater likelihood of sustaining a HSI.

Ethnicity

Being of African American or Aboriginal decent has been associated with an increased risk of HSIs in a small number of studies (Copland et al., 2009, Opar et al., 2012, Orchard, 2001, Verrall et al., 2001). It is believed that Aboriginal descendants are predisposed to an increase in anterior pelvic tilt which lengthens the hamstring muscles exposing the muscles to greater forces in lengthened positions and increasing the risk of strain injuries (Copland et al., 2009, Opar et al., 2012, Verrall et al., 2001, Woods et al., 2004). A study investigating

the risk factors associated with HSIs in rugby union reported no evidence of ethnicity increasing the risk of HSI (Brooks et al., 2006). However, as the supporting literature is small and somewhat equivocal, it remains unclear if ethnicity is a risk factor for hamstring strains.

Previous Hamstring Strain

Amongst all the risk factors associated with HSIs, previous hamstring strains are the greatest predictor of future HSIs (Arnason et al., 2008, Bennell et al., 1998, Copland et al., 2009, Opar et al., 2012, Orchard, 2001, Verrall et al., 2001, Garrett, 1996). Athletes are two to six times more likely of sustaining a recurring HSI in their lifetime, with most strains occurring within two months of returning to sport (Arnason et al., 2008, Bennell et al., 1998, Copland et al., 2009, Opar et al., 2012, Orchard, 2001, Verrall et al., 2001). The high reoccurrence rate of HSIs across multiple sports suggests that there is inappropriate rehabilitation processes in place and athletes are returning to full activity without the necessary treatment (Arnason et al., 2008, Bennell et al., 1998, Opar et al., 2012, Verrall et al., 2001). Scar tissue formation, changes in the biomechanics of athletes running gait, reduced flexibility, long term atrophy of the injured hamstring muscles and insufficient strengthening of the hamstrings may result from the initial injury and all can be contributing factors that ultimately lead to an increased risk of additional HSIs (Brughelli and Cronin, 2008, Croisier, 2004, Croisier et al., 2002, Opar et al., 2012, Orchard et al., 1997, Orchard, 2001, Jonhagen et al., 1994, Silder et al., 2008, Worrell et al., 1991). Full determination of the cause of the recurrent HSI is difficult to ascertain due to the retrospective nature of the observations. Therefore, it is not known if these factors are the cause or the result of the injury.

Modifiable Risk Factors

Strength Imbalances

Strength imbalances of the hamstring muscle group such as imbalances for hamstring strength between limbs, imbalances between quadriceps and hamstring strength and decreases in eccentric hamstring strength have long been proposed as risk factors for HSIs (Brooks et al., 2006, Copland et al., 2009, Opar et al., 2012, Sugiura et al., 2008). Strength imbalances between limbs, termed hamstring bilateral asymmetry, have been associated with increases in HSIs. Studies suggest that asymmetries greater than 10%, 8% and 15% for track and field athletes, ARF athletes and soccer players, respectively, increase the risk of occurrence of a hamstring strain (Croisier et al., 2008, Heiser et al., 1984, Orchard et al., 1997, Opar et al., 2012). Maintaining training on the uninjured limb for the hamstring muscles can produce strength differences when returning from injury as a result of muscle atrophy in the injured limb and muscle hypertrophy in the uninjured limb which can then

increase the risk of future HSIs as there is an ever present strength asymmetry between limbs (Brooks et al., 2006, Opar et al., 2012, Brughelli and Cronin, 2008).

Strength imbalances between quadriceps and hamstrings muscles may also predispose athletes to HSIs. The relative strength of these muscles has been termed the H : Q ratio and reported as the concentric strength of both hamstrings and quadriceps ($H : Q_{conv}$) (Opar et al., 2012). More recently the quadriceps and hamstring strength ratio has evaluated and popularised as the concentric strength of the quadriceps versus the eccentric strength of the hamstrings ($H : Q_{func}$) to more accurately simulate the relationship to running requirements of the muscle groups (Croisier et al., 2002, Croisier et al., 2008, Opar et al., 2012, Sugiura et al., 2008). It is believed that forceful concentric contraction of the quadriceps during the early swing phase of the running gait may have the potential to exceed the mechanical eccentric limits of the hamstrings (Opar et al., 2012). Therefore, it is recommended that athletes should maintain a $H : Q_{func}$ ratio above 0.89 to significantly reduce the risk of HSIs (Croisier et al., 2008), although there is limited research to support this value and it is not known if the results can transfer to other sports. Related factors that can result in a low $H : Q_{func}$ ratio are the results of previous hamstring strains as athletes may continue to train the uninjured quadriceps muscles which results in larger strength differences between the muscle groups (Opar et al., 2012, Brooks et al., 2006). Normalising H : Q ratios has led to significant decreases in HSI occurrences compared to athletes who do not alter the imbalances (Croisier et al., 2008). Therefore, as a precautionary measure, taking time to normalise the H : Q ratio may provide additional benefit in reducing the risk of a HSI.

Fatigue

Fatigue induced by match play and training sessions has been matched to performance decrements and has often been associated with the causation of HSIs (Heiser et al., 1984, Mair et al., 1996). Several studies have supported this claim, identifying the latter parts of training and match play as the most common time for HSIs to occur (Brooks et al., 2006, Garrett, 1996, Woods et al., 2004, Timmins et al., 2014).

There are several reasons given for the belief of fatigue being a risk factor for HSIs. Timmins et al. (2014) demonstrated a significant reduction in BF eccentric strength and surface electromyography (sEMG) activity following repeated sprint protocols to simulate match fatigue. This fatigue-related decrease in BF eccentric muscle activity and strength may then place the hamstrings at risk of a strain injury as there is an associated decrease in neural signalling so the hamstrings are not able to respond to potential straining movements as quickly as possible. While fatigue induces a decrease in eccentric strength, it has been reported that there is little or no change in concentric strength of the quadriceps which then creates a H : Q ratio imbalance during fatigued states (Small et al., 2009). Furthermore,

following an acute bout of intermittent isometric contractions of the knee flexors and extensors, there is an associated delay in signal transmission of the knee flexors along with a longer recovery period compared to that of the knee extensors (Conchola et al., 2013).

Fatigue may also cause an acute decrease in proprioception, where athletes underestimate hamstring length during running (Opar et al., 2012). A reduction in proprioception could result in the athletes perceiving a normal hamstring length when it is actually repeatedly over-lengthening, elevating the risk of a HSI occurring. Other factors such as a change in the athletes running technique, fatigue induced reductions in concentration and coordination of muscle recruitment patterns have been suggested as plausible risk factors but insufficient testing has been completed to support the claims (Opar et al., 2012).

Flexibility

A lack of hamstring flexibility has been proposed to increase the risk of sustaining a HSI despite the lack of comprehensive, prospective studies on the topic, as most studies evaluate the effect of implementing a flexibility protocol to training sessions (Brooks et al., 2006, Opar et al., 2012, Witvrouw et al., 2004). Orchard (2001) found that in ARF players, most hamstring strains occurred during maximal sprinting efforts or when bending forward to pick up the ball at speed. The bending forward motion would lead to suggestions that an increase in hamstring flexibility would reduce the rate of this occurrence. There is however, conflicting evidence as to the effect of hamstring flexibility in reducing strain injuries due to the unstandardised hamstring flexibility testing protocols utilised to date. Limited evidence suggests greater hamstring flexibility can decrease the risk of HSI (Brooks et al., 2006, Opar et al., 2012, Prior et al., 2009). Some studies believe that an increase in hamstring flexibility may have the ability to reduce the risk of a strain injury due to an increase in the muscle-tendon units ability to absorb energy and a less passive recoil from tighter hamstrings (Gabbe et al., 2002, Witvrouw et al., 2004). Testing methods used to determine the effect of hamstring flexibility in reducing HSIs is confounding with little scientific evidence available to support the claim. Some studies use inadequate flexibility programs where stretches are held for only 10 seconds and others perform stretches during the warm-up only which is a conventional prevention tool used in most sports but is not supplemented with further stretching sessions.

Hamstring Strain Prevention

The most effective way to prevent hamstring strains is to identify the most common risk factors associated with the strain and make adaptations to reduce the risk factor(s) as much as possible. This means that while there are some common principles all athletes should follow to minimise the risk of hamstring injury, the relative emphasis may differ between

athletes in different sports with different risk factors. The considerations for preventative measures are based on the evidence provided for risk factors causing HSIs.

Warm-Up

Prescription of a concise warm-up including passive and active warm-ups and muscle stretching before training and completion have long been supported as effective injury-prevention strategies (Kujala et al., 1997, Petersen and Hölmich, 2005), although there is limited evidence to illustrate the effect of these activities in reducing muscle strains. Intervention studies prescribing warm-up protocols consisting of contract-relax flexibility training and active warm-up stretches showed no change in the reduction of HSIs (Arnason et al., 2008, Opar et al., 2012). Petersen and Hölmich (2005) have suggested from their results that the inclusion of static stretches before exercise may help to prevent HSIs but there is little supporting evidence and no significant results were found. Therefore, a well prescribed warm-up is recommended to prevent injuries but the use of other interventions may have more impact on specifically preventing hamstring strains.

Match Specific Training

Due to the belief that match fatigue may increase the risk of sustaining a HSI, recommendations have been made to incorporate more high-intensity, interval and anaerobic training to more accurately reflect the demands of match play (Verrall et al., 2005, Petersen and Hölmich, 2005). By training in a fatigued state, the belief is that the athletes become more aware of muscle movements and are able to maintain a normal biomechanical gait to help prevent hamstring strains. A key concern with this approach is that there may be a risk for training-related HSIs due to the nature of the training patterns which may then predispose athletes to match-related HSIs. More supportive evidence into the effect of high intensity, match specific training to prevent hamstring strains is warranted.

Hamstring Strength Training

Eccentric Training

There is considerable supporting evidence that eccentric strength training of the hamstrings is an effective protocol to prevent the occurrence of HSIs (Arnason et al., 2008, Askling et al., 2003, Brooks et al., 2006, Engebretsen et al., 2008, Gabbe et al., 2006b, Mjøltnes et al., 2004, Opar et al., 2012). Brockett et al. (2001) originally developed an eccentric strengthening exercise now referred to the NHE (Brooks et al., 2006). The NHE has shown to reduce the rate of occurrence of HSIs in multiple sports when implemented into training programs (Arnason et al., 2008, Askling et al., 2003, Brooks et al., 2006, Engebretsen et al., 2008, Gabbe et al., 2006b, Mjøltnes et al., 2004, Opar et al., 2012). A recent meta-analysis has concluded that eccentric hamstring strength training with a protocol

that allows for good compliance is successful in reducing the rate of HSIs (Goode et al., 2015).

The Nordic Hamstring Exercise

The NHE is a bodyweight resistance training exercise that requires athletes to start in a kneeling position, with the ankles typically held down by a partner throughout the movement, allowing them to gradually lower their upper body towards the ground, resisting the movement as much as possible by eccentrically contracting the hamstrings, (Brughelli and Cronin, 2008, Opar et al., 2012). The NHE movement pattern is demonstrated in Figure 4.

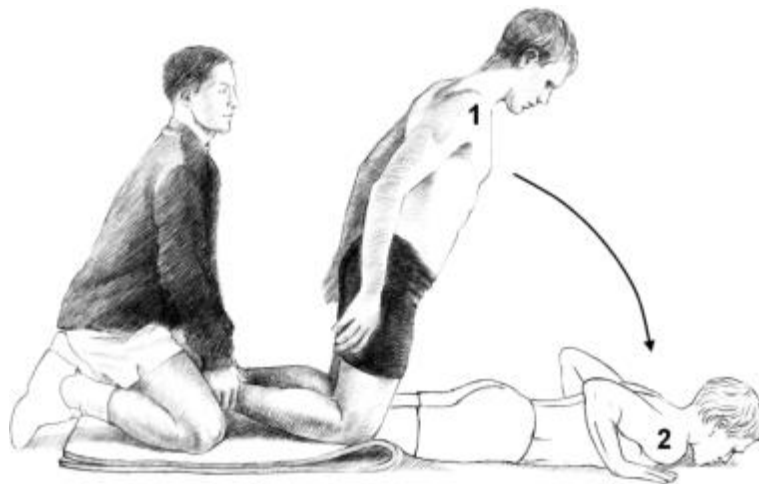


Figure 4: The Nordic hamstring exercise demonstrated from the starting position (1) to the finishing position (2), where the entire movement is resisted through eccentric contraction of the hamstrings as much as possible. Adapted from (Arnason et al., 2008).

The NHE was developed as it is partner assisted, removes the need for expensive equipment to perform eccentric training, can be done anywhere and doesn't require multiple spotters as used during conventional eccentric training (Brughelli and Cronin, 2008). The NHE is able to increase eccentric strength of the hamstrings which is a suggested mechanism of reducing the rate of HSIs (Brooks et al., 2006, Brughelli and Cronin, 2008, Mjøl̈snes et al., 2004, Opar et al., 2012).

Implementation of NHE has shown no improvement in reducing the rate of HSIs in ARF players and soccer players, although both interventions reported poor compliance to the study with the use of high-volume, low-frequency protocols (Engebretsen et al., 2008, Gabbe et al., 2006b). Studies that have implemented the NHE on a large number of subjects using the more conventional conditioning practice described by Mjøl̈snes et al. (2004), have seen significant reductions in HSIs compared to control groups. Reductions in hamstring strains as high as 65% have been demonstrated in elite soccer and rugby teams compared to a control group of a previous year with no NHE training (Arnason et al., 2008, Brooks et al.,

2006). It is interesting to note that the implementation of the NHE did not reduce the rate of HSI recurrence for previously injured hamstrings (Arnason et al., 2008). This has been supported in amateur soccer players ($n = 579$) throughout the beginning of a season where NHE implementation significantly reduced the number of HSIs with no effect on the severity when a HSI occurred (van der Horst et al., 2015).

For elite Australian football players performing the NHE as a strength assessment exercise on a novel field testing device (Figure 5), players that went on to sustain a HSI throughout the season had significantly weaker knee flexor strength at the start and end of pre-season training compared to the athletes that did not sustain a HSI (Opar et al., 2015a). The elevated probability of sustaining a HSI associated with older athletes or those with a previous HSI can be offset by higher levels of eccentric hamstring strength measured via the NHE (Opar et al., 2015a).



Figure 5. The novel field testing device used to assess eccentric knee flexor strength during the NHE. The device measures force through uniaxial load cells located on each individual ankle brace.

A number of studies have suggested that by virtue of its bilateral nature, the use of NHE may subject the athlete to asymmetries in hamstring strength as athletes may favour their dominant limb therefore, creating greater strength imbalances and perhaps even increasing injury risk to the weaker limb (Clark et al., 2005, Iga et al., 2012, Brughelli and Cronin, 2008). For example, Clark et al. (2005) reported that 4 weeks of NHE training resulted in greater asymmetries in hamstring strength between limbs than was observed pre-training. Therefore, there should be considerations made as to how this can be eliminated during training. In contrast, a ten week NHE intervention study noted significant reductions in between limb strength asymmetries (10.3% and 4.69% at the start and end of training intervention respectively) measured via isokinetic dynamometry in female rugby union players (Anastasi and Hamzeh, 2011). A new device using the NHE is capable of measuring force outputs for both limbs which could potentially remove the risk of creating asymmetries as each repetition force output can be monitored (Opar et al., 2013a).

In summary, the literature offers quite strong support for the use of NHE training as a preventative measure for HSIs. Some modifications have been suggested in order to eliminate any confounding factors; use the NHE in conjunction with a full hamstring resistance training program, perform more eccentric exercises at a greater hamstring length and monitor hamstring asymmetries that may result from the NHE (Arnason et al., 2008, Brughelli and Cronin, 2008, Iga et al., 2012, Opar et al., 2013a). However, one issue has been how to quantify any potential changes in eccentric hamstring strength asymmetries easily and accurately within training sessions.

Eccentric Strength Training Alternatives

An alternative to the NHE is Flywheel training, where the athletes perform eccentric and concentric actions on the hamstring muscles in a lying-leg curl position to simulate the requirements during running. Flywheel training has been reported to significantly reduce the occurrence of HSIs as well as increasing athletes strength and speed compared to a control group (Askling et al., 2003). It is suggested that it is more beneficial to incorporate flywheel training into sporting programs as it has additional benefits on top of injury prevention such as strength and speed increases. Flywheel training has shown to significantly reduce the occurrence of HSIs although the device is expensive and not easily accessible for most team sports as is the NHE. The NHE is a cheaper alternative to Flywheel training and much more applicable to a field based assessment for team sport environments, since similar benefits have been associated the NHE it is a much more practical assessment tool for team sports.

Recommendations for the inclusion of exercises such as; eccentric backward steps, stiff leg deadlift and single leg deadlifts could eccentrically strengthen the hamstrings at a greater length of tension than the NHE (Brughelli and Cronin, 2008). However, a lack of research as to the efficacy of these exercises does not support any assumptions made about the exercises in terms of being more superior than the NHE in reducing the rate of HSIs.

Exercise Selection

It is recommended that between limb knee flexor strength imbalances should be targeted and removed by strengthening protocols to reduce the risk of HSIs. When strength imbalances have been addressed, whether that be between hamstrings and quadriceps or between the left and right hamstring, the adjusted athletes show significant improvement in terms of lower HSI rates compared to those without intervention to address these strength imbalances (Croisier et al., 2008). Consideration should be taken to determine if there are strength imbalances in relation to the hamstrings to help prevent HSIs as much as possible.

Magnetic resonance imaging testing has recently revealed that the BF long head and SM are significantly less active during heavy eccentric leg curls compared to the ST and gracilis

muscles (Ono et al., 2010b, Opar et al., 2012). When examining the prone leg curl, ST seems to be most activated compared to the BF and SM (Schuermans et al., 2014). This is similar to a recent EMG study finding that the ST is significantly more activated than other hamstring muscles during the NHE (Bourne et al., 2015a). Although it does not target the BF long head specifically, it is possible that the NHE preferentially stimulates ST adaptations that effectively protect the BF during running by an enhanced load bearing capacity (Bourne et al., 2015a). To further support this claim, it has been noted that ST has the highest levels of muscle activity during the terminal swing phase, a commonly associated phase with HSIs (Schuermans et al., 2014). Therefore, if the ST is most active during the time of occurrence for hamstring strains, it could be beneficial to target the ST with strengthening exercises in order to provide a greater support framework surrounding the knee flexors to help reduce the incidence of HSIs.

Strengthening exercises that have been suggested to target the BF are stiff leg deadlifts and Romanian deadlifts. Ono et al. (2010a) concluded that the BF long head is more selectively activated in the stiff leg deadlift. While McAllister et al. (2014) concluded that greater muscle activation for the BF (as well as ST and SM) occurred during the eccentric Romanian deadlift compared with the eccentric prone leg curl.

Taken together, these findings suggest that although the BF is not targeted specifically during the NHE, the chronic performance of the NHE can reduce the risk of HSIs, perhaps through an increase in activation and force output of the ST. Incorporating the NHE with other eccentric hamstring exercises such as the Romanian deadlift that targets the BF may have the greatest effect in reducing the risk of HSIs, however, further research is required to support this claim.

Rehabilitation Corrections

The high risk associated with previous hamstring strains being a causative factor for future HSIs would suggest that adaptations in the rehabilitation process must be re-evaluated. Croisier (2004) has emphasised the need to avoid errors in training modalities and rehabilitation procedures in order to reduce the high number of recurring HSIs in sport. Results of recurring hamstring strains indicate that players may be exposed to maximal efforts too early in their return to sport (Brooks et al., 2006, Croisier, 2004, Worrell et al., 1991). A recent study involving elite Australian football players found that previously injured athletes displayed smaller increases in eccentric hamstring strength following pre-season training compared to athletes that had no previous HSI (Opar et al., 2015b). It was interesting to note that the smaller increases in eccentric strength were not restricted to the previously injured limb, but to both limbs.

Extra consideration should be taken to ensure athletes do not create strength imbalances from continuation of training uninjured limbs, especially eccentric hamstring strength deficits (Brooks et al., 2006, Brughelli and Cronin, 2008, Opar et al., 2012). In order to maximise the benefits of eccentric training, it has been suggested that knee flexion movements should be performed in a seated position in order to ensure full lengthening of the hamstrings during the movement (Schmitt et al., 2012). Complete rehabilitation of the injured limb with greater consideration to strength deficits is suggested to help reduce the risk of re-injury for hamstring strains.

Hamstring Inhibition Following Injury

Recently, it has been proposed that there may be residual side effects of a hamstring strain that may relate to a decrease in neural activation of the injured limb, although evidence of this phenomenon is somewhat limited (Fyfe et al., 2013, Opar et al., 2012, Opar et al., 2013b, Opar et al., 2013c, Sole et al., 2012). Deficits in eccentric strength have been identified for athletes that have returned to full training and competition following a HSI, suggesting a residual adaptation from injury that has not been addressed (Croisier et al., 2002, Lee et al., 2009, Bourne et al., 2015a). sEMG studies involving athletes with previous BF strains that have undergone full rehabilitation have demonstrated that the injured limb has significantly lower activity levels during eccentric but not concentric contractions, with such differences not seen in the uninjured limb or in the healthy control group (Opar et al., 2013b, Opar et al., 2013c). There was also a delay in the rate of torque development for the injured limb compared to the uninjured limb and the control group, suggesting a decrease in neural activation following injury and a reduced ability to quickly contract in response to an unexpected perturbation (Opar et al., 2013c).

Explanations as to why these events may still occur in fully rehabilitated limbs may be due to several factors. Muscular pain observed from the incidence of the HSI has the ability to alter central nervous function and may result in a restriction of EMG activity during contraction of the injured limb (Fyfe et al., 2013, Opar et al., 2013b). It has been suggested that reductions in hamstring activation levels reflects a protective mechanism to prevent further tissue damage that may result from high force contractions (Opar et al., 2012). Along with the associated pain of the limb injury, a reduction in voluntary activation is noted for athletes with previous hamstring strains, presumably to reduce tissue loading soon after injury (Fyfe et al., 2013). Hamstring muscles following strain injuries may have residual persistent atrophy that is still present even in rehabilitated limbs, with this having the potential to alter the limbs innervation following injury (Silder et al., 2008). More studies into the effect of hamstring inhibition following hamstrings strains is required to confirm that the

injured limbs may present with reductions in activation that may lead to potential re-injury of the limb.

Augmented Feedback

Psychological strategies have been suggested to improve overall quality of training and have reported increases in strength, power and skill-based tasks when associated with complex movements related to sport (Argus et al., 2011, Jung and Hallbeck, 2007, Kim and Kramer, 1997, McNair et al., 1996, Tod et al., 2005). Incorporating psychological techniques into training can be done using intrinsic or extrinsic techniques such as, self-talk and 'psyching up' for intrinsic techniques and visual and verbal feedback for extrinsic techniques (Argus et al., 2011, Jung and Hallbeck, 2007, McNair et al., 1996, Tod et al., 2005, Wulf et al., 2010). Although studies have identified improvements in performance with the use of psychological techniques, the exact mechanisms resulting in the improvements are unclear but it is believed to be due to a combination of enhanced focus of attention, neuromuscular activation, levels of arousal and improved skill performance and learning (Argus et al., 2011, Jung and Hallbeck, 2007, Kim and Kramer, 1997, McNair et al., 1996, Tod et al., 2005, Wulf et al., 2010). AF describes extrinsic psychological training techniques that provide additional information to the athlete compared to that which can be obtained from intrinsic knowledge of their performance and is classified into two feedback types; knowledge of results and knowledge of performance (Kilduski and Rice, 2003, Phillips et al., 2013). The primary outcome of psychological training strategies such as AF is to improve performance through changes in motor learning which can result in the ability for an individual to acquire a motor skill with a relatively permanent change through practice or experience (Gokeler et al., 2013).

The application of AF during varying tasks has resulted in mostly positive results that have the ability to improve performance. The use of visual and verbal feedback applied separately during maximal voluntary contraction of a grip strength dynamometer resulted in an increased peak grip strength in untrained participants (Jung and Hallbeck, 2007). Verbal feedback given after every bench throw performed by elite rugby union players resulted in small effect size improvements in mean peak power compared to when no feedback (NFB) was provided (Argus et al., 2011).

AF following a drop jump immediately increased jump height with the greatest long term improvement in the group receiving constant feedback (Keller et al., 2014a). Similar results have been found for counter movement jumps, with the groups receiving AF improving their results more than groups with only an external focus of attention and internal focus of attention (Keller et al., 2014b). These studies suggest that for a mixed population, there is some potential in utilising AF techniques to increase performance. Real-time visual feedback of force outputs during eccentric knee flexor and extensor movements resulted in increased

gravity-corrected eccentric moment outputs (Kellis and Baltzopoulos, 1996). Kim and Kramer (1997) found that participants training with visual feedback during maximal knee extension efforts demonstrated a greater rate of learning compared to those who trained without feedback and were able to retain the greatest force production for a longer period compared to the control group with NFB.

While most previous research supports the use of AF techniques in helping to improve player performance it is yet to be associated with an increase in performance retention. Knowledge of results following every practice trial does improve immediate performance but it is suggested that it does not lead to a greater retention of a skill that is practiced (Kilduski and Rice, 2003). It is possible that there are some negative responses to incorporating AF into training scenarios as providing knowledge of results may reduce the athletes ability to rely on intrinsic feedback due to neurological sensory impairments, therefore, the athlete is more dependent on AF to improve a skill (Kilduski and Rice, 2003). Most studies that evaluate the effectiveness of psychological strategies have experimental designs with little resemblance to the applied sport environment of which most of the findings are generalised to, as they contain novice participants and are conducted in a laboratory setting.

AF does have the potential to help improve limb asymmetries. Real-time biomechanical feedback may be beneficial in improving persistent between limb asymmetries associated with rehabilitating patients following anterior cruciate ligament reconstruction surgery (Gokeler et al., 2013). A small scale study investigating the effects of using real-time velocity feedback during squat jumps over a six week training period suggested that greater training adaptations can be obtained with the use of real-time feedback during resistance training settings, although, no significant differences were seen as the sample size was small (Randell et al., 2011). These studies suggest that the results may be transferable to eccentric hamstring strength asymmetries and combining AF techniques during eccentric hamstring training may have the ability to reduce limb asymmetries and increase the rate of strength gains, although this has not been examined to date.

Conclusion

The introduction of new game formats to cricket has placed the modern day player under increased training and playing loads compared to previous years. Trends have started to appear from the increase in player loading resulting in more injuries across all formats of cricket and across multiple countries. Amongst the increase in injuries in cricket, HSIs are considered to be the most commonly occurring injury to cricket players, with some suggesting that it is the elite pace bowler who is at the greatest risk of sustaining a HSI. HSIs remain the most common injury in multiple sporting codes that involve high intensity running and cricket is no different. The limited evidence surrounding when and how HSIs occur

during cricket calls for more research and understanding in this area. Once the cause of HSIs in cricket is better understood, specific preventative measures can be put in place to limit the occurrence of HSIs.

Preventative measures such as increased eccentric knee flexor strength training are the most evidence-based strategies to reduce the number of HSIs. If complete training programs can be implemented with more eccentric hamstring strengthening exercises and more effective rehabilitation programs and policies are developed for athletes with previous HSIs, there is potential for the number of occurring HSIs to decline. Focusing on limiting hamstring asymmetries, in particular, eccentric strength asymmetries, appears promising for a reduction in future HSIs in sport.

Due to the limited understanding of the causes of HSIs in cricket and the effect of increasing demands on cricket players hamstring asymmetries, the current research project has been developed to measure eccentric knee flexor strength asymmetries in a variety of cricket player groups of different skill levels. The project will look to provide further knowledge of cricket player's eccentric knee flexor strength measured during the NHE and whether combining AF in the form of real-time performance feedback can help to reduce eccentric knee flexor strength asymmetries. The aim of the study was to collect normative data on cricket players from elite, sub-elite and school level competitions to determine if an increase in playing level increases the risks of having greater strength asymmetries and determine whether AF can help to reduce any inter-limb differences in force outputs. This study relates to the existing literature as there is limited information regarding hamstring asymmetries in cricket players and little is known about the effects of increasing competitive playing levels. The application of AF during a sport specific environment is very limited and this study aims to improve on existing literature.

Chapter Three: Comparison of Eccentric Knee Flexor Strength and Asymmetries Across Elite, Sub-elite and School Level Cricket Players

Abstract

Objectives. The objective of this study was to compare eccentric knee flexor strength and bilateral asymmetries in elite, sub-elite and school level cricket players; and to determine if playing position and limb role influenced these eccentric knee flexor strength indices. It was hypothesised that elite level cricket players will present with greater eccentric knee flexor strength and asymmetries, further, bowlers will present with the greatest between limb strength asymmetries.

Background. There has been a continual increase in injury rates in cricket, with hamstring strain injuries (HSIs) being the most prominent. Eccentric knee flexor weakness and bilateral asymmetries are major modifiable risk factors for future HSIs. However, there is a lack of data relating to eccentric hamstring strength in cricket at any skill level.

Methods. Seventy four male cricket players of three distinct skill levels performed three repetitions of the Nordic hamstring exercise on the experimental device. Strength was assessed as the absolute and relative mean peak force output for both limbs, with bilateral asymmetries. Differences in mean peak force outputs between skill level and playing positions were measured.

Results. There were no significant differences between elite, sub-elite and school level athletes for mean peak force and bilateral asymmetries of the knee flexors. There were no significant differences observed between bowlers' and batters' mean peak force and bilateral asymmetries. There were no significant differences between front and back limb mean peak force outputs.

Conclusion. Skill level, playing position and limb role appeared to have no significant effect on eccentric knee flexor strength and bilateral asymmetries. Future research should seek to determine whether eccentric knee flexor strength thresholds are predictive of HSIs in cricket and if specific eccentric knee flexor strengthening can reduce these injuries.

Introduction

Cricket is a team sport involving a side of 11 players with specialist batters, bowlers and one wicket-keeper. Originating from test match cricket which was typically played over 5 days between two teams with unlimited overs, limited overs cricket (50 overs per team) and T20 (20 overs per team) games lasting 7-8 hours and 3 hours respectively are also now widely played (Cannonier et al., 2013). As a result of these new formats, elite level cricket players are now playing more cricket each year, with the intensity of these games also appearing to increase (Frost and Chalmers, 2014).

Injury rates appear to be increasing for elite cricketers in many countries, with HSIs often the most commonly occurring injury (Frost and Chalmers, 2014, Orchard et al., 2002, Orchard et al., 2011, Orchard et al., 2006, Stretch, 2003). Less injuries are reported for junior compared to senior players, with most junior injuries associated with ball contact (Finch et al., 2010). Elite pace bowlers may be at higher risk of HSIs than batters and wicket-keepers (Orchard et al., 2011). The pace bowler's greater HSI risk may reflect their greater total running and sprint distances (Petersen et al., 2010) as well as the intense loads placed on the front leg during ball release when bowling, whereby the knee flexors act to rapidly decelerate the total body's forward momentum resulting from their run-up. Player position (batter or bowler) and limb dominance (front or back leg) during batting, bowling and throwing may therefore have an impact on HSI risk in cricket. However, the symmetry, or lack thereof of knee flexor function is yet to be documented in cricket, unlike other sports (Bourne et al., 2015b, Opar et al., 2015a).

Risk factors that have been associated with HSIs in the wider sports medicine literature include; increased age, previous hamstring injuries, lack of hamstring flexibility, muscle fatigue and hamstring muscle weakness or asymmetry (Brooks et al., 2006, Croisier et al., 2002, Croisier et al., 2008, Gabbe et al., 2006a, Jonhagen et al., 1994, Opar et al., 2012, Orchard et al., 1997, Verrall et al., 2001). In particular, eccentric knee flexor strength deficits and bilateral eccentric knee flexor strength asymmetries have been linked to an increased risk of HSIs (Brooks et al., 2006, Croisier et al., 2008, Opar et al., 2012, Orchard et al., 1997). A novel field testing device has recently been developed to measure eccentric knee flexor strength and strength asymmetries via uniaxial load cells during the NHE (Opar et al., 2013a, Opar et al., 2015a). Elite Australian football players with eccentric knee flexor strength below 256N and 279N at the start and end of pre-season training, respectively, have approximately a 3 to 4 fold increased risk of sustaining a HSI (Opar et al., 2015a), further confirming the importance of eccentric knee flexor strength in the prevention of HSIs. Additionally, the elevated probability of sustaining a HSI for older athletes or those with a previous HSI can be offset with greater eccentric knee flexor strength (Opar et al., 2015a). Recent studies using the novel field testing device in elite Australian football and rugby union present

somewhat contrasting results on the predictive ability of between limb asymmetries and eccentric knee flexor strength for HSIs. Elite Australian football players with a between limb strength asymmetry of $\geq 10\%$ did not have an increased risk of sustaining a HSI (Opar et al., 2015a). This contrasts with a study involving rugby union players where a between limb strength asymmetry $\geq 15\%$ and $\geq 20\%$ had an increased risk of sustaining a HSI by 2.4 and 3.4 fold respectively (Bourne et al., 2015b). Such studies suggest that between limb strength asymmetries may be an issue in some sports but not others. Additional studies have found that asymmetries greater than 10%, 8% and 15% for track and field athletes, Australian football players and soccer players respectively, increase the risk of occurrence of a HSI (Croisier et al., 2008, Heiser et al., 1984, Orchard et al., 1997, Opar et al., 2012).

Given the lack of data relating to eccentric knee flexor strength in cricket at any level, the asymmetrical demands of cricket batting, bowling and throwing as well as the increasing prevalence of HSIs in elite cricket, the primary purpose of this investigation was to determine the effect different player parameters had on eccentric knee flexor strength and bilateral asymmetries in elite, sub-elite and school level cricket players. The secondary purpose was to determine if playing position and limb role influenced eccentric knee flexor strength or the magnitude of asymmetries. It was hypothesised that elite level cricket players would present with greater eccentric knee flexor strength and asymmetries than sub-elite and school level players, further, bowlers would present with greater between limb strength asymmetries than the batters.

Materials & Methods

Participants

Seventy four male cricket players (16 elite level, 32 sub-elite level and 26 school level) with at least two years of experience in the sport provided written informed consent before participating in the study (Appendices A and B). All participants were recruited from their associated cricket club with the coach's approval. Athletes with a previous and/or current lower limb injury that had not yet been fully rehabilitated were not included in the study. Ethical approval was granted by the Bond University Human Research Ethics Committee (RO1824).

Research Design

A cross-sectional comparative study design was used with all testing performed at the start of pre-season training before the commencement of a training session and at the start of the training week. This was to be consistent with previous studies using the experimental device (Bourne et al., 2015b, Opar et al., 2015a) and to control for any potential differences in training that occur between the playing groups over the course of the season. All

participants completed a familiarisation session in which they performed two sets of three repetitions of the NHE on the novel field testing device (Figure 6) while being provided with coaching cues for correct technique.



Figure 6. The novel field testing device used to assess eccentric knee flexor strength during the NHE. The device measures force through uniaxial load cells located on each individual ankle brace.

One week later, they were reassessed to determine eccentric knee flexor strength and bilateral asymmetries on the novel field testing device with high to moderate test-retest reliability for force measurements when the NHE was performed bilaterally (Opar et al., 2013a). Prior to the main testing session, a submaximal warm-up set of the NHE of three repetitions (first repetition at ~50% of maximum perceived exertion, second repetition at ~70% of maximum perceived exertion and the third repetition at ~90% of their maximum perceived exertion) was performed before the athletes completed one set of three maximal efforts with one minute rest between sets and 15 seconds inter-repetition rest.

Eccentric Knee Flexor Strength Assessment

Strength was assessed as the peak force output measured on the field testing device (Opar et al., 2013a). All participants were asked to kneel on a padded board with their ankles secured immediately superior to the lateral malleolus. Separate securing braces were attached to custom made uniaxial load cells (Delphi Force Measurements) fitted with wireless data acquisition capabilities (Mantracourt Electronics Ltd). Ankle braces were secured to the testing device via a pivot system to ensure force was always measured through the long axis of the load cells. Athletes were instructed to gradually lean forward at the slowest possible speed while maximally resisting the tendency to fall with both limbs, keeping the trunk and hips in a neutral position throughout the movement with hands placed across the chest (Opar et al., 2013a). Verbal encouragement and technique coaching was provided throughout each repetition to promote maximal efforts.

Data Analysis

Force data for both left and right limbs during the NHE were logged to a personal computer at 50Hz through a wireless receiver (Mantracourt Electronics Ltd). Mean peak force (N) was calculated for both limbs for the three maximal repetitions. The relative peak force was calculated by dividing the mean peak force (N) by the participant's body mass (kg) so to account for any differences on body-mass between participant groups. The between limb imbalance in eccentric knee flexor force was calculated as a left:right limb ratio of the mean peak force as recommended, using log transformed raw data followed by back transformation (Impellizzeri et al., 2008).

Statistical Analysis

All statistical analysis was performed using SPSS version 20.0 (IBM corporation). Means and standard deviations (SD) for age, height, body mass, absolute and relative eccentric knee flexor strength and eccentric knee flexor strength imbalances are presented. If data was not normally distributed, as assessed by Shapiro-Wilks test for normality, log transformation was performed. Log transformed data was then back transformed to represent true values. Data was compared between all three playing groups (elite, sub-elite and school) and further compared based on their self-nominated playing specialisation (bowler or batter) with Cohen *d* values provided. Small effect sizes were classified as > 0.2 , moderate effect size > 0.5 and a large effect size ≥ 0.8 (Cohen, 1988). One way analysis of variance with a Tukey post-hoc test was used to compare mean peak force output (combined average of left and right limbs) and limb asymmetry between the three groups (elite, sub-elite and school). An independent t-test compared the mean peak force and limb asymmetry between playing positions (bowlers and batters). Paired t-tests were performed comparing front and back leg mean peak force outputs, where front leg was considered the leg most forward at the point of ball release when bowling and throwing and in the normal batting stance for batters. Within-session variability of peak force and limb asymmetry was quantified via the coefficient of variation, calculated for all three groups based on the three maximal repetitions. Significance was set at $P < 0.05$.

Results

The physical characteristics of each skill level and playing position are described in Table 3. Increases in skill level were associated with significantly increased player age, height and weight.

Table 3. Physical characteristics of participants in each skill level and playing position.

	Elite (n=16)	Sub-elite (n=32)	School (n=26)	Combined (n=74)
Age (yr)	24.5 ± 4.5	21.5 ± 4.2*	15.7 ± 1.0*†	20.1 ± 4.9
Height (cm)	186.2 ± 9.5	184.2 ± 6.9	178 ± 7.2*	183.1 ± 7.9
Mass (kg)	86.3 ± 8.1	83.1 ± 10.3	69.4 ± 11.0*†	79.0 ± 12.3

	Bowlers (n=42)	Batters (n=32)
Age (yr)	20.1 ± 4.7	20.1 ± 5.2
Height (cm)	184.2 ± 8.4	181.7 ± 7.1
Mass (kg)	80.3 ± 13.0	77.3 ± 11.3

Data presented as mean ± standard deviation. * Significantly different to elite level athletes. † Significantly different to sub-elite level athletes

There were no significant differences between elite, sub-elite and school level athletes for absolute mean peak force (elite vs sub-elite $d = 0.07$; sub-elite vs school $d = 0.32$; elite vs school $d = 0.42$; $P > 0.05$), relative mean peak force (elite vs sub-elite $d = -0.10$; sub-elite vs school $d = -0.42$; elite vs school $d = -0.55$; $P > 0.05$) and bilateral asymmetries (elite vs sub-elite $d = -0.34$; sub-elite vs school $d = 0.21$; elite vs school $d = -0.11$; $P > 0.05$). 24 athletes (32.4%) had bilateral limb asymmetries $\geq 15\%$, and 14 (18.9%) of these athletes had asymmetries $\geq 20\%$. Furthermore, Table 4 indicates there were no significant differences observed between bowler's and batter's absolute ($d = -0.11$; $P > 0.05$) and relative mean peak force ($d = -0.29$; $P > 0.05$) and bilateral asymmetries ($d = 0.04$; $P > 0.05$). Of the 24 athletes with limb asymmetries $\geq 15\%$, 14 (33.3%) were bowlers and 10 were batters (31.3%). Nine bowlers (21.4%) and 5 batters (15.6%) had limb asymmetries $\geq 20\%$. There were no significant differences between front and back limb absolute mean peak force outputs ($299 \pm 79\text{N}$ and $303 \pm 71\text{N}$; $d = -0.05$; $P > 0.05$) and relative mean peak force ($3.83 \pm 1.03\text{N.kg}^{-1}$ and $3.84 \pm 0.84\text{N.kg}^{-1}$; $d = -0.01$; $P > 0.05$) (see Figure 7).

Table 4. Mean peak force outputs and relative mean peak force outputs with bilateral limb asymmetries of knee flexors during the NHE for all three groups; elite, sub-elite and school level and playing positions; bowlers and batters.

	Absolute Mean Peak Force (N)	Relative Mean Peak Force (N.kg ⁻¹)	Bilateral Asymmetry (%)
Elite	313 ± 67	3.65 ± 0.89	11.5 ± 8.6
Sub-elite	308 ± 77	3.74 ± 0.96	15.1 ± 12.2
School	285 ± 68	4.11 ± 0.77	12.6 ± 11.6
Bowler	297 ± 77	3.74 ± 0.97	13.7 ± 10.3
Batter	305 ± 65	3.99 ± 0.76	13.2 ± 12.5

Data presented as mean ± standard deviation.

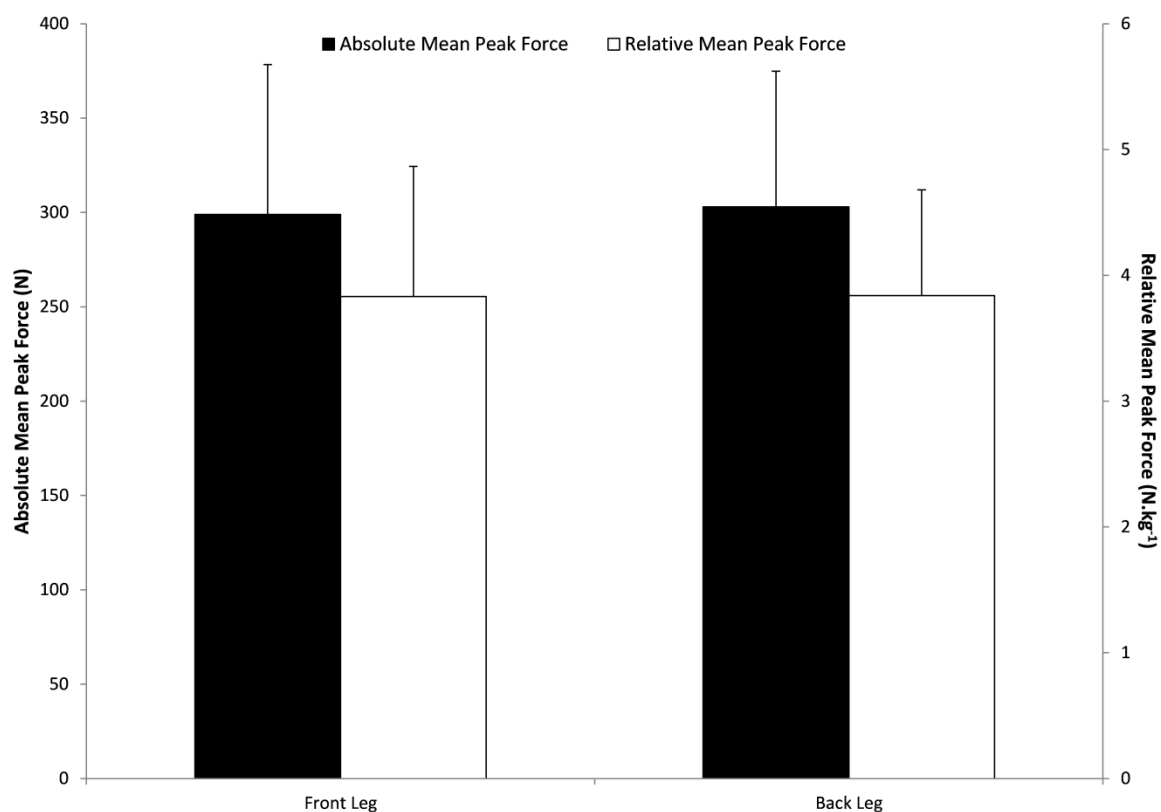


Figure 7. Mean peak force outputs (N) and relative mean peak force outputs (N.kg⁻¹) for combined group (n = 74) comparing front leg to back leg. Error bars depict the standard deviation of the mean.

Discussion

To the best of our knowledge, this is the first paper to measure eccentric knee flexor strength in cricket players of any skill level. As HSI rates are increasing in cricket (Frost and Chalmers, 2014, Orchard et al., 2011, Orchard et al., 2006), this study may be the first to identify the potential role of eccentric knee flexor strength and bilateral asymmetries in predisposing cricket players to such injury.

The lack of any significant difference in eccentric knee flexor strength or asymmetry between skill levels was surprising. Elite players were expected to be stronger as they should have greater experience in performing knee flexor strengthening exercises and they place greater loads on their hamstrings as a result of their greater running and sprinting distances (Petersen et al., 2010). There was only a small effect size between sub-elite and school level athletes and a small to moderate effect size between elite and school level athletes for absolute mean peak force. Relative mean peak force demonstrated a small to moderate effect size between sub-elite and school level athletes and a moderate effect size between elite and school level athletes.

While cricket players possessed ~80% of the eccentric knee flexor strength of rugby union players of similar levels (367N, 389N and 343N for elite, sub-elite and under 19 athletes respectively) (Bourne et al., 2015b). The differences in eccentric knee flexor strength between skill levels of rugby union players appears similar in magnitude to that of the current study in cricket. However, there was a significant difference in bilateral eccentric knee flexor force outputs between the sub-elite and under 19 athletes in rugby union. Therefore, differences between the cricket groups for mean peak force were expected considering the mean age of the school athletes (15.7 ± 1 year) is lower than the rugby under 19 athletes.

Due to the greater physical demands in elite compared to sub-elite and schoolboy sport, the results of this study and that of Bourne et al. (2015b) may suggest that additional specific eccentric knee flexor exercises may be required in elite cricket and rugby to reduce their high prevalence of HSIs. Support for this suggestion may be found in soccer where the addition of the NHE significantly reduced HSI rates (Arnason et al., 2008, Askling et al., 2003). Further, the fact that the school level athletes possess greater relative mean peak force compared to elite and sub-elite athletes may explain why the occurrences of HSIs in junior cricket are much lower compared to elite athletes who are playing and training under greater physical demands with a reduced capacity to protect the knee flexors.

There was no significant difference in eccentric knee flexor strength or bilateral asymmetries between bowlers and batters. Additionally, bowlers were found to have less relative mean peak force compared to batters ($3.74 \pm 0.97\text{N.kg}^{-1}$ and $3.99 \pm 0.76\text{N.kg}^{-1}$, respectively), even though it could be proposed that bowlers should be able to produce

greater relative force as they are exposed to more eccentrically demanding knee flexor actions during the bowling action. Specifically, elite pace bowlers may be more prone to HSIs than elite batters due to the high-intensity eccentric loads placed on the hamstrings of the front leg at ball release during bowling (Orchard et al., 2011) and their greater sprinting distances (Petersen et al., 2010). This suggests that elite pace bowlers may be the playing group most in need of additional eccentric knee flexor strengthening exercises. The relatively low average bilateral asymmetry for both playing positions suggests that the game is not subjecting athletes to chronic limb asymmetries. However, greater consideration for eccentric knee flexor strengthening exercises may need to be implemented for bowlers at an elite and sub-elite level to help combat the high incidence rates of HSIs.

It is unclear whether such additional eccentric knee flexor training should focus on reducing bilateral asymmetries or increasing the strength of both knee flexors in elite cricketers. Elite Australian football players with an eccentric knee flexor force output below 256N at the start of pre-season training were at an increased risk of sustaining a HSI (Opar et al., 2015a), within the 74 participants of this study, 21 (28.4%) had a mean peak force output below 256N, and when separated into playing positions, 14 bowlers (33.3%) and 7 batters (21.9%) had mean peak force outputs below 256N. Results of the current study indicated similar mean levels of bilateral limb asymmetries for bowlers (13.7%) and batters (13.2%) and across all three skill levels (11.5-15.1%). This was further supported with similar proportions of athletes at each skill level with bilateral limb asymmetries $\geq 15\%$ (31.3%, 34.4% and 30.8% for elite, sub-elite and school level groups respectively). Elite Australian football players with a bilateral limb asymmetry of up to 20%, as measured on the same testing device as the current study, did not increase the risk of sustaining a HSI (Opar et al., 2015a). This contrasts with rugby union, where a 2.4 and 3.4 fold increase of HSI risk occurred with asymmetries of $\geq 15\%$ and $\geq 20\%$ respectively (Bourne et al., 2015b). While the contribution of knee flexor strength asymmetry on HSI rates seems to differ between sports, further prospective studies involving cricket players throughout an entire season may be required to better understand this relationship.

The present data suggest there was no significant difference between absolute and relative mean peak force for front and back limbs. It was expected that front limb would be stronger in both playing positions as batters associate their front leg with the greatest amount of use and bowler's front legs are associated with the greatest eccentric demands during the bowling action at ball release. The exact causes for similar front and back limb forces across all participants are unknown and it may come down to multiple influences that may differ between each player.

The current study is limited by the sample sizes for each group. Larger samples may allow greater certainty of the effect of skill level, playing position and leg dominance on knee

flexor limb strength and asymmetries. The cross-sectional nature of the data also limits the inferences that can be drawn from the data. It is acknowledged that the time of testing may not truly represent playing positions. However, it is believed as all athletes are experienced in the game of cricket and their playing position any chronic asymmetries between limbs would likely still be present at the start of pre-season training.

Conclusion

There appears to be no significant differences between eccentric knee flexor strength or between limb strength asymmetries for elite, sub-elite and schoolboy players during the NHE. Furthermore, playing position (batter or bowler) or leg role (front or back) appears to have no significant effect on eccentric knee flexor strength and between limb strength imbalances for cricket players. Further research is required to prospectively monitor cricket players to determine if eccentric knee flexor strength or between limb strength asymmetries is a predictor of hamstring injury and if eccentric knee flexor strengthening exercise programs may reduce injury rates in cricket.

Chapter Four: Effect of Acute Augmented Feedback on Bilateral Limb Asymmetries and Eccentric Knee Flexor Strength During the Nordic Hamstring Exercise

Abstract

Objectives. Determine the acute effects of real-time visual augmented feedback (AF) provided during the Nordic hamstring exercise (NHE) in reducing between limb knee flexor strength asymmetries and increasing bilateral knee flexor strength outputs. It was hypothesised that real-time visual feedback provided during the NHE would reduce between limb knee flexor strength asymmetries and increase eccentric knee flexor strength.

Background. AF can improve overall movement quality and increase strength and power related to sport performance. Eccentric knee flexor weakness and between limb asymmetries can predispose athletes to an increased risk of hamstring strain injuries (HSIs). It is unknown whether acute feedback can reduce between limb eccentric knee flexor strength differences or increase bilateral knee flexor strength.

Methods. Using a cross over study design, forty four male cricket players from two skill levels performed two NHE sessions with and without the aid of visual feedback of force production. Differences in mean peak force outputs and between limb asymmetries were compared between the two conditions.

Results. There was a significant increase in mean peak force production when feedback was provided compared to no feedback (NFB) but no significant difference in between limb asymmetry for feedback or NFB. Increases in force production for the feedback condition were a result of increased weak limb force contribution compared to the strong limb.

Conclusion. Real-time visual feedback provided during the NHE resulted in significantly increased eccentric knee flexor force. Therefore, the chronic performance of NHE with feedback may reduce HSI risk by increasing eccentric knee flexor strength, especially of the weaker limb.

Introduction

Psychological strategies have been suggested to improve overall quality of training and increase strength, power and skill-based tasks when associated with complex movements related to sport (Argus et al., 2011, Jung and Hallbeck, 2007, Kim and Kramer, 1997, McNair et al., 1996, Tod et al., 2005). Incorporating psychological techniques into training can be done using intrinsic (self-talk and 'psyching up') or extrinsic (visual and verbal AF) (Argus et al., 2011, Jung and Hallbeck, 2007, McNair et al., 1996, Tod et al., 2005, Wulf et al., 2010). While the exact mechanisms resulting in the improvements with psychological techniques remain unclear, it may reflect a combination of enhanced focus of attention, neuromuscular activation, levels of arousal and improved skill performance and learning (Argus et al., 2011, Jung and Hallbeck, 2007, Kim and Kramer, 1997, McNair et al., 1996, Tod et al., 2005, Wulf et al., 2010).

By definition, AF provides additional information to the athlete compared to that which could be obtained from intrinsic knowledge of their performance alone. The application of AF during varying tasks has resulted in positive results that have the ability to improve performance. The use of visual and verbal feedback applied separately during maximal voluntary contraction of a grip strength dynamometer resulted in acute increases in peak grip strength in a general population (Jung and Hallbeck, 2007). Verbal feedback given after every bench throw performed by elite rugby union players resulted in an acute small effect size increase in mean peak power compared to when NFB was provided (Argus et al., 2011). Further, the chronic effect of AF has been shown to increase jump height in untrained (Keller et al., 2014a) and elite rugby union players (Randell et al., 2011). Limited research also suggests that AF may also be used to reduce a number of injury risk factors. Specifically, Cronin et al. (2008) reported that verbal feedback of athletes jumping technique during a spike jump significantly reduced elite volleyball player's vertical ground reaction force which is a known risk factor for landing related injuries. Visual feedback of force outputs during isokinetic dynamometry has also resulted in greater acute peak torque during concentric (Brian et al., 2000) and eccentric knee flexion contractions (Kellis and Baltzopoulos, 1996).

Given the positive effects of using feedback on force output, incorporating visual feedback during strengthening exercises that have been shown to reduce injury rates may help to increase the rate of learning and improve the effectiveness of such exercises. HSIs are one of the most commonly occurring injuries in cricket (Orchard et al., 2011), Australian football (Hrysomallis, 2013), rugby union (Brooks et al., 2006), American football (Cross et al., 2010) and soccer (Arnason et al., 2004). Factors that have been proposed to increase the risk of HSIs in the wider sports medicine literature include; increased age, previous HSI, lack of hamstring flexibility, muscle fatigue, shorter bicep femoris fascicle lengths and knee flexor muscle weakness or asymmetry (Brooks et al., 2006, Croisier et al., 2002, Croisier et

al., 2008, Gabbe et al., 2006a, Jonhagen et al., 1994, Opar et al., 2012, Orchard et al., 1997, Verrall et al., 2001, Timmins et al., 2015). In particular, eccentric knee flexor strength deficits and bilateral eccentric hamstring strength asymmetries have been linked to an increased risk of HSIs (Croisier et al., 2002, Opar et al., 2012, Orchard et al., 1997). There is considerable supporting evidence that eccentric strength training of the hamstrings is an effective protocol to prevent the occurrence of HSIs (Arnason et al., 2008, Askling et al., 2003, Brooks et al., 2006, Engebretsen et al., 2008, Gabbe et al., 2006b, Petersen et al., 2011).

The NHE has been shown to reduce the rate of occurrence of HSIs in multiple sports when implemented into training programs (Arnason et al., 2008, Brooks et al., 2006, Engebretsen et al., 2008, Gabbe et al., 2006b). With the recent development of a field testing device that quantifies eccentric knee flexor strength via the NHE (Opar et al., 2013a), there is potential for field based improvements in eccentric knee flexor force production and reductions in limb asymmetries. Considering the comparably large number of HSIs occurring in cricket, particularly to elite level pace bowlers (Frost and Chalmers, 2014, Mansingh et al., 2006, Orchard et al., 2011, Stretch, 2003), research is needed to determine the optimal approach to reduce any between limb strength asymmetries and increase eccentric knee flexor strength in these athletes.

The primary purpose of the present investigation was to determine the acute effect of real-time visual feedback provided during the NHE in reducing bilateral knee flexor strength asymmetries. The secondary purpose of the current investigation was to determine whether acute real-time visual feedback provided during the NHE would significantly increase bilateral knee flexor strength outputs. It was hypothesised that real-time visual feedback provided during the NHE would reduce between limb knee flexor strength asymmetries and increase eccentric knee flexor strength.

Methods

Participants

A total of 44 male cricket players with at least two years of experience in the sport provided written informed consent before participating in the study (Appendix A and C). Athletes with a previous and/or current lower limb injury that had not yet been fully rehabilitated were not included in the study. Ethical approval was granted by the Bond University Human Research Ethics Committee before the commencement of data collection (RO1824).

Research Design

A crossover study design was used with all participants required to perform a familiarisation session involving three sets of three NHE repetitions with 15 seconds inter-

repetition rest at a submaximal effort. The familiarisation session was performed to ensure correct movement sequencing and technique when performing the NHE. Testing was performed to determine eccentric knee flexor strength and bilateral asymmetries on a novel field testing device previously assessed for reliability (Opar et al., 2013a). Testing was performed one week after the familiarisation sessions, with the assessments performed at the beginning of the training week, before any training was performed. A second testing session was completed the same time the following week. All testing was done at the start of pre-season training for each team. Testing sessions followed standardised procedures (Opar et al., 2013a) and included a submaximal warm-up set of the NHE of three repetitions followed by one minute rest before participants were asked to perform two sets of three repetitions with 15 seconds inter-repetition rest and four minutes rest between sets. This was done to be consistent with previous studies using the experimental device (Bourne et al., 2015b, Opar et al., 2015a) and to control for any potential differences in training that occur between the playing groups over the course of the season.

Table 5. Feedback sequencing for four groups

	Testing Session 1	Testing Session 2
Augmented Feedback	School 1	School 2
	Sub-elite 1	Sub-elite 2
No Feedback	School 2	School 1
	Sub-elite 2	Sub-elite 1

Real-Time Visual Feedback

Table 5 shows the sequencing for testing for all four teams. Teams were randomly assigned to two groups, receiving feedback in the first testing session (FB1) or second testing session (FB2) as a crossover study design. In order to control for any differences in performance that may occur between the two sessions spaced one week apart, visual feedback was only provided in the second set. The provision of visual feedback for the second set only, ensured that we were able to quantify the within session effect of AF on the outcome measures. The augmented feedback was provided as a real-time force output on a display screen that was positioned directly in front of the participant. Participants were instructed to “reduce limb asymmetries as much as possible using the real-time visual force outputs displayed in front them”. Figure 8 shows the display that athletes viewed during the NHE where the yellow line represents the force output of the left limb and the purple line represents the force output of the right limb.

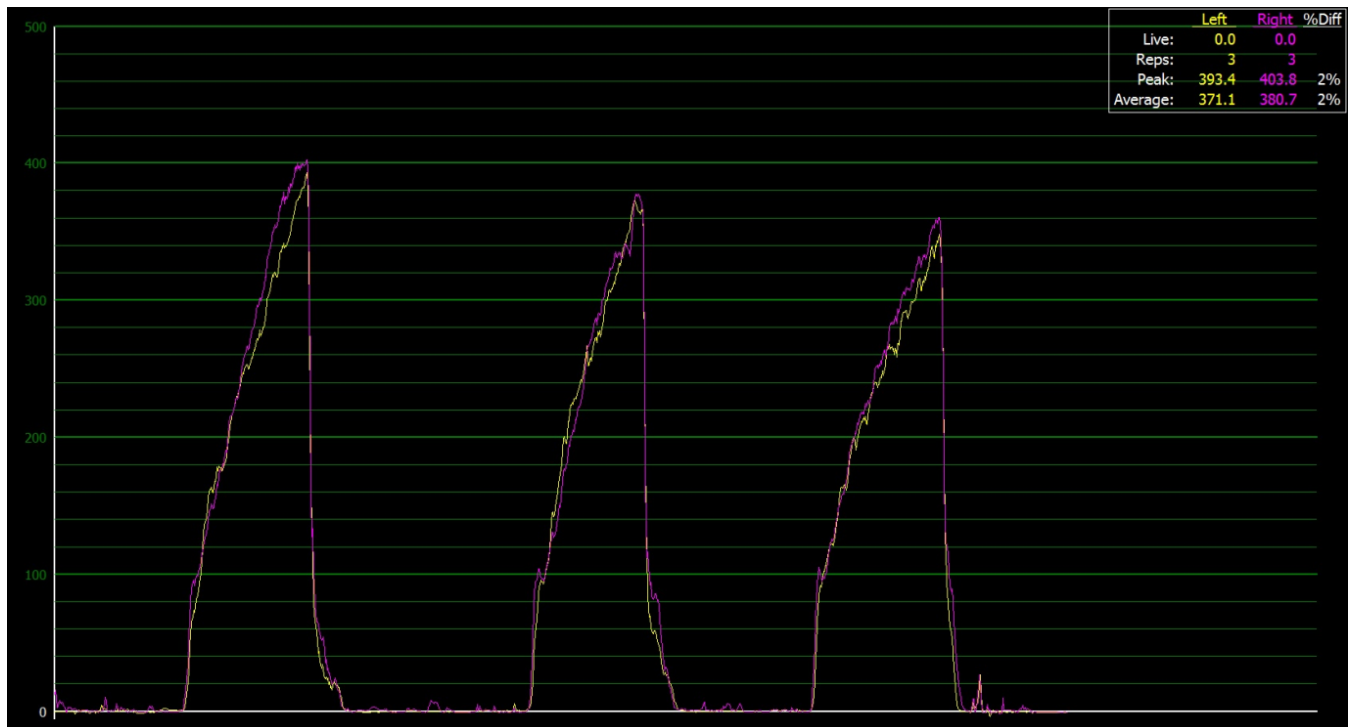


Figure 8. Real-time display of eccentric knee flexor force outputs during the NHE for three repetitions. Yellow line represents the left limb and purple line represents the right limb.

Eccentric Knee Flexor Strength Assessment

Strength was assessed as the peak force output on the field testing device (Opar et al., 2013a). All participants were asked to kneel on a padded board with the posterior portion of their ankles secured immediately superior to the lateral malleolus. Separate securing braces were attached to custom made uniaxial load cells (Delphi Force Measurements) fitted with wireless data acquisition capabilities (Mantracourt Electronics Ltd). Ankle braces were secured to the testing device via a pivot system to ensure force was always measured through the long axis of the load cells. Athletes were instructed to gradually lean forward at the slowest possible speed while maximally resisting the tendency to fall with both limbs, keeping the trunk and hips in a neutral position throughout the movement with hands placed across the chest (Opar et al., 2013a). Verbal encouragement and technique coaching was provided throughout each repetition to promote maximal efforts. When performing the test with real-time feedback, each athlete's weaker limb was identified to ensure they knew which limb force output to focus upon. Regardless of the provision of feedback or NFB, successful trials of the NHE required the athletes to reach a distinct peak force followed by a rapid decline in force representing the point at which the athlete was no longer able to resist the effect of gravity acting upon the segment above the knee joint.

Data Analysis

Force data for both left and right limbs during the NHE were logged to a personal computer at 50Hz through a wireless receiver (Mantracourt Electronics Ltd). Mean peak force (N) was calculated for both limbs for the three maximal repetitions. The between limb imbalance in eccentric knee flexor force was calculated as a left:right limb ratio of the mean peak force as recommended, using log transformed raw data followed by back transformation (Impellizzeri et al., 2008). Log transformed asymmetry values were used when testing for significance. Mean peak force outputs were used when testing for significance between weak and strong limbs.

Statistical Analysis

All statistical analysis was performed using SPSS version 20.0 (IBM corporation). Means and standard deviations (SD) of age, height, body weight, eccentric knee flexor strength and strength imbalances are presented. If data was not normally distributed, as assessed by Shapiro-Wilks test for normality, log transformation was performed. Log transformed data was then back transformed to represent true values. Data was compared between the two conditions (FB1 and FB2) assessing differences in limb asymmetries and mean peak force outputs with and without feedback. This was done using an independent t-test on the average of both testing sessions (with and without feedback) to ensure there was no carryover effect, followed by an independent t-test on treatment differences to test for period effect and an independent t-test on period differences to show treatment effect. The magnitude of the differences in the force outputs between feedback conditions were also examined using Cohen *d* effect size values. Small effect sizes were classified as $d > 0.2$, moderate effect size $d > 0.5$ and a large effect size $d \geq 0.8$ (Cohen, 1988). Further analyses of mean peak force outputs were performed to determine the cause of any potential increase in force with feedback. This was calculated by comparison of weak and strong limb force outputs using a paired t-test for both conditions (with and without feedback). Significance for all comparisons was set at $P < 0.05$.

Results

The 44 participants consisted of 21 school athletes (mean age, 15.7 ± 1.0 years; mean height, 179.1 ± 7.6 cm; mean body mass, 68.5 ± 10.6 kg) and 23 sub-elite athletes (mean age, 21.2 ± 3.9 years; mean height, 184.0 ± 7.0 cm; mean body mass, 83.2 ± 9.4 kg). There were no significant differences between the characteristics of the two treatment groups, FB1 ($n = 24$; mean age, 18.3 ± 3.5 years; mean height, 181.7 ± 8.7 cm; mean body mass, 76.1 ± 12.6 kg) and FB2 ($n = 20$; mean age, 18.9 ± 4.6 years; mean height, 181.6 ± 6.3 cm; mean body mass, 76.2 ± 12.4 kg).

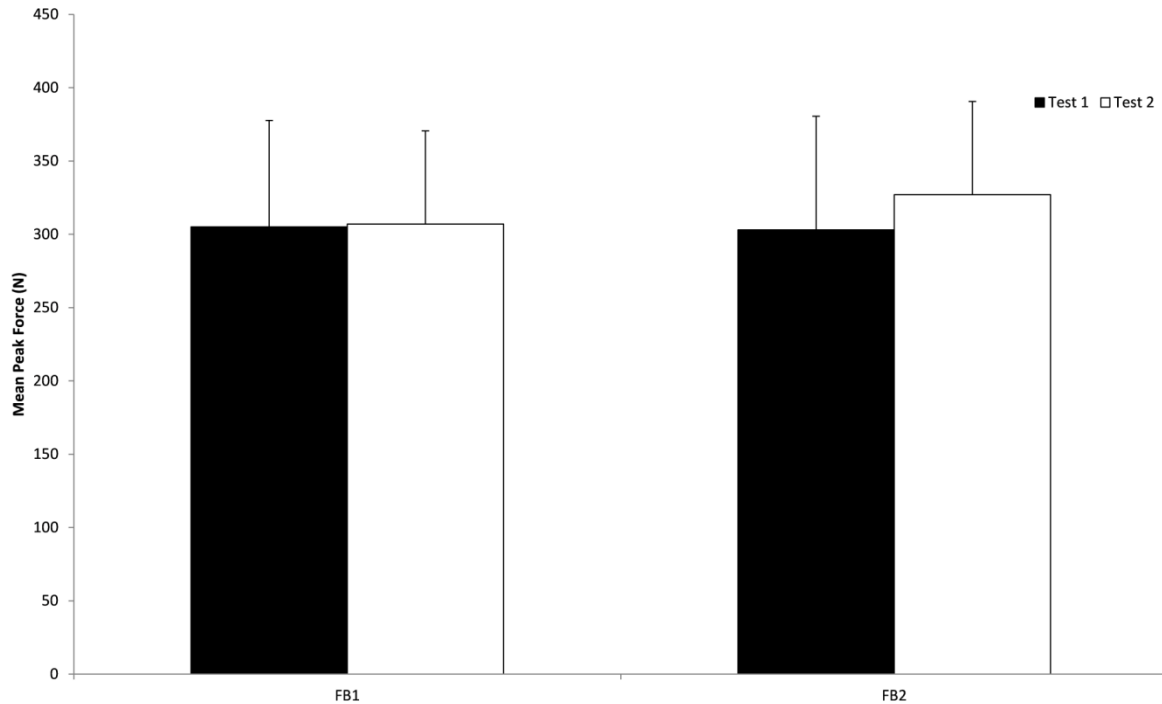


Figure 9. Mean peak force outputs for both feedback groups during the two testing sessions. FB1 were provided real-time feedback during testing session 1; whereas FB2 were provided real-time feedback during testing session 2. Error bars depict the standard deviation of the mean.

Figure 9 and 10 show the average force outputs and asymmetries during each feedback condition for the two groups. Force for the FB1 group was $305 \pm 73\text{N}$ and $307 \pm 64\text{N}$ ($d = -0.03$) at test 1 and 2, respectively, while the force for the FB2 group was $303 \pm 78\text{N}$ and $327 \pm 72\text{N}$ ($d = 0.32$) at test 1 and 2, respectively. The average bilateral limb asymmetry for the FB1 group was $14.1 \pm 12.4\%$ and $17.3 \pm 15.46\%$ ($d = -0.23$) at test 1 and 2, respectively, while the FB2 group's average bilateral limb asymmetry was $13.4 \pm 9.8\%$ and $11.2 \pm 11.2\%$ ($d = 0.21$) at test 1 and 2, respectively.

There was a significant increase in mean peak force production when feedback was provided compared to NFB following the crossover (mean difference, 21.7N ; 95% confidence interval [CI], 0.2N to 42.3N ; $d = 0.61$; $p = 0.048$). However, there was no significant difference in between limb asymmetry for feedback and NFB conditions within all subjects (mean difference, 5.7% ; 95% CI, -2.8% to 14.3% ; $d = 0.41$; $p = 0.184$). Figure 11 shows the changes in the force output of the weak and strong limb that occurred when feedback was provided. There was a significant increase in force for the weak limb when feedback was provided ($284 \pm 65\text{N}$ vs $299 \pm 72\text{N}$, for NFB and feedback trials, respectively; mean difference, 15.0N ; 95% CI, 1.6N to 28.5N ; $d = 0.22$; $p = 0.029$). There was no significant difference in force for the strong limb in either feedback condition ($327 \pm 77\text{N}$ vs $331 \pm 78\text{N}$, for NFB and feedback trials, respectively; mean difference, -4.0N ; 95% CI, -

16.6N to 8.3N; $d = 0.05$; $p = 0.504$). When examined on an individual athlete basis, 64% of the athletes increased their weak limb force when feedback was provided while maintaining a similar force output of the strong limb.

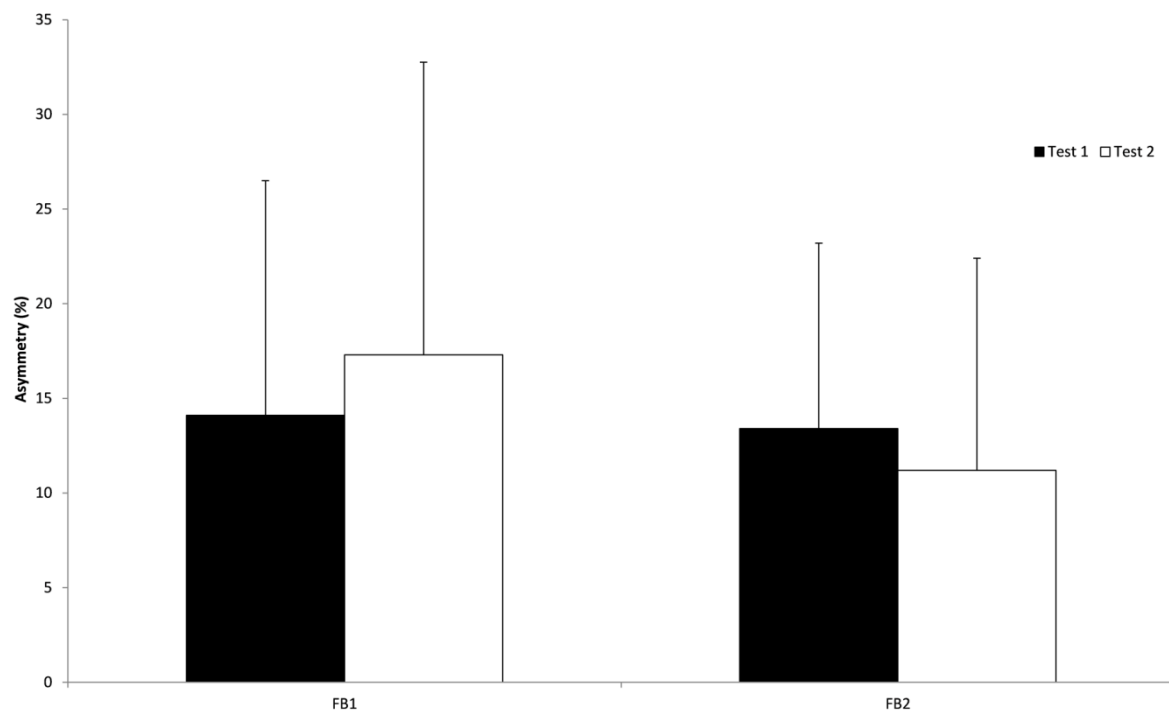


Figure 10. Average bilateral limb asymmetry for both feedback groups during the two testing sessions. FB1 were provided real-time feedback during testing session 1; whereas FB2 were provided real-time feedback during testing session 2. Error bars depict the standard deviation of the mean.

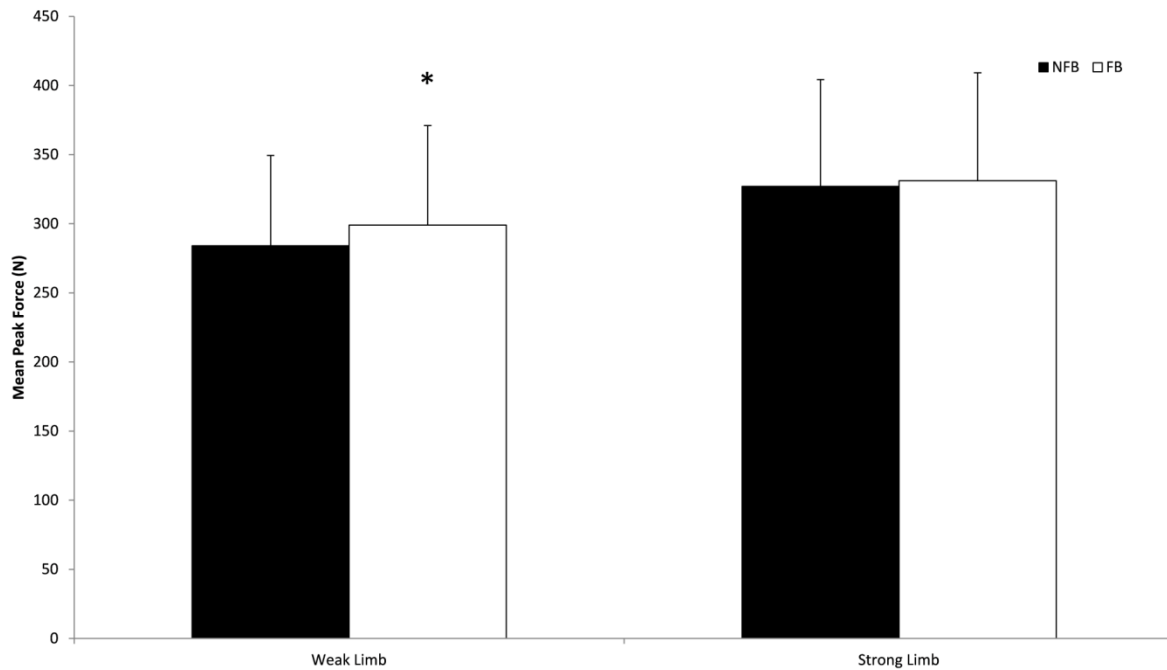


Figure 11. Mean peak force changes for weak and strong limbs with and without feedback. *Significantly different to weak limb for NFB protocol, $P < 0.05$. Error bars depict the standard deviation of the mean.

Discussion

The purpose of the present investigation was to assess the effects of real-time visual feedback during the NHE in reducing bilateral eccentric knee flexor strength asymmetries and increasing eccentric knee flexor mean peak force outputs. This is the first study to apply real-time visual feedback during the NHE to assess the effect on a variety of eccentric knee flexor force outputs. The results of the present study suggest that the acute use of feedback may provide some significant, moderate effect improvements in eccentric knee flexor force production and that further research examining the chronic application of feedback is warranted. The current data suggest real-time visual feedback had no significant effect on bilateral eccentric knee flexor strength asymmetries when expressed as absolute percentages. A secondary analysis of bilateral eccentric knee flexor strength changes demonstrated that there was a significant increase in the weaker limb force output compared to the stronger limb under the feedback condition during the NHE.

Real-time visual feedback during the NHE had no significant effect on reducing the absolute percentage of between limb strength asymmetries, although effect size analyses indicated a small to moderate decrease in absolute limb asymmetry when feedback was provided. The lack of a significant decrease in the between limb strength asymmetries observed with the acute provision of feedback could be due to a number of factors. First, it

may be that multiple sessions of feedback are required for participants to alter their usual force production strategies and therefore significantly decrease their between limb strength asymmetries. Second, as previously described by Opar et al. (2013a), the experimental device used in this study has greater reliability in assessing force outputs (moderate to high test-retest reliability) compared to assessing between limb force asymmetries (moderate test-retest reliability).

In the present study, real-time visual feedback during the NHE resulted in a significant increase in mean peak force production compared to NFB. Of even greater interest was the significant increase in the weaker limb's peak force production when feedback was applied, with no significant change observed for the stronger limb. This suggests that when athletes were provided feedback, the significant increase in mean force and the trend (small to moderate effect size) for reductions in bilateral limb asymmetry were a result of increased output of the weaker limb and not due to a decrease in the stronger limb force. This finding is of interest as the only instruction provided to the athletes was to "reduce limb asymmetries as much as possible using the real-time visual force outputs". Therefore it appears that the majority of athletes (64%) achieved this goal by increasing the force output of their weaker limb. If the acute increase in eccentric force for the weaker limb observed in one training session in the study can be repeated across multiple sessions, it is likely to result in an increase in strength of the weaker limb over the course of multiple weeks. If such feedback could be provided over multiple training sessions, this control strategy may significantly reduce between limb asymmetries and increase the eccentric knee flexor strength, particularly within the weaker limb since feedback has been shown to significantly increase athlete's acute (Argus et al., 2011, Jung and Hallbeck, 2007) and chronic (Keller et al., 2014a, Randell et al., 2011) force outputs.

To the best of our knowledge, this is the first study to use AF in the form of real-time visual feedback to reduce bilateral limb strength asymmetries and increase eccentric knee flexor force production during the NHE. The results of this present study provide further insight into the beneficial use of AF as a performance tool. Considering the large number of HSIs occurring in soccer, American football, Australian football, rugby union and cricket (Frost and Chalmers, 2014, Mansingh et al., 2006, Orchard et al., 2002, Orchard et al., 2006, Arnason et al., 2004, Braham et al., 2004, Brooks et al., 2006, Cross et al., 2010, Gabbe et al., 2002) and the well documented benefits of increasing eccentric knee flexor strength and reducing bilateral limb asymmetries for the prevention of HSIs (Arnason et al., 2008, Askling et al., 2003, Brooks et al., 2006, Engebretsen et al., 2008, Gabbe et al., 2006b, Petersen et al., 2011), prevention strategies need to be implemented targeting these modifiable risk factors. Since the use of AF during the NHE acutely increased weak limb force outputs in the present study, it may facilitate greater strength gains and therefore justify the inclusion of AF

in future intervention studies. As the elevated risk of sustaining a HSI for older athletes or those with a previous HSI can be offset with greater eccentric knee flexor strength (Opar et al., 2015a), the use of feedback during the NHE may help to reduce HSI rates in these populations.

The current study may be limited by the heterogeneity of the sample group. More homogeneous groups with one skill level of the same sport may show more of a significant difference in the ability for AF to reduce between limb eccentric knee flexor asymmetries as the reliability of percentage scores such as the between limb asymmetry is often less than the directly measured outcome, such as, eccentric force. It is understood that elite athletes show less adaptations and performance enhancements to external stimuli (Randell et al., 2011), so the inclusion of elite athletes in future studies may better show the true magnitude of effect on the skill level with the greatest reported HSIs.

Conclusion

In conclusion, the use of real-time visual feedback during the NHE resulted in a non-significant but small to moderate effect size decreases in between limb eccentric knee flexor force asymmetries and significantly increased eccentric knee flexor force for sub-elite and school level cricket players. Real-time visual feedback resulted in an increase in weak limb force contribution during the NHE which may have future implications in the way bilateral strengthening exercises are prescribed for HSI prevention. Further research within more homogenous populations may be required to better determine the potential for real-time visual feedback to reduce bilateral eccentric knee flexor force asymmetries in elite and non-elite athlete groups at risk of HSIs. Future studies examining the chronic effect of real-time visual feedback and how this may impact on injury risk factors and injury rates are also required.

Chapter Five: Discussion

This discussion chapter endeavours to bring together the literature that was reviewed and the findings of the two research studies in order to provide an overview of the thesis and how it contributes to the current body of knowledge. Specifically, this chapter includes a summary of the literature reviewed, the main results of the current studies in the thesis, a discussion synthesising the results of the studies in relation to the wider literature, the practical applications of the results, the limitations to the current thesis and direction for future research.

Elite cricket has undergone a number of changes following the development of T20 cricket. T20 cricket brings a faster, action packed version of cricket to the audience which has resulted in greater interest from players to play as many games as possible. The increased number of matches played per year, decrease in rest periods between matches and greater accumulation of high intensity training and competition workloads has ultimately led to a spike in player demand and therefore increased risk of injury (Frost and Chalmers, 2014, Orchard et al., 2011, Stretch, 2003). However, it is interesting to note that the most common injuries in elite cricket across multiple countries, namely HSI are not common in junior level cricket players (Finch et al., 2010, Orchard et al., 2011).

For elite level cricket players, lower limb injuries appear to be the most common (Frost and Chalmers, 2014, Orchard et al., 2011). While these lower limb injuries appear to affect bowlers, batters and fielders during training and competition, pace bowlers may be more susceptible to sustaining these injuries than other playing positions (Frost and Chalmers, 2014, Orchard et al., 2002, Orchard et al., 2011, Orchard et al., 2006, Stretch, 2003). Of all the lower limb injuries, HSIs are among the most commonly occurring injury in elite level cricket, with pace bowlers more at risk than the other playing positions (Frost and Chalmers, 2014, Mansingh et al., 2006, Orchard et al., 2002, Orchard et al., 2011, Stretch, 2003). Dissimilar to elite level cricket, the most commonly occurring injuries in junior cricket are associated with ball contact and appear to affect all playing positions relatively equally (Finch et al., 2010).

The cause of most pace bowling injuries may be associated with prior workloads. Specifically, the high incidence of pace bowling injuries in first class matches may be a result of athletes competing in T20 competitions immediately prior to returning to first class games. There are fewer injuries recorded in T20 but as a result of accumulated fatigue and high intensity workloads the injuries occur during the first class competition (Orchard et al., 2011). While there is no prospective evidence to support the claim, it is believed that most HSIs in pace bowlers occur during the end of the bowling phase, with most strains occurring on the non-bowling side (front leg) due to the high eccentric loads (Orchard et al., 2011).

The wider literature indicates that most HSIs occur during forceful repetitive contractions of the hamstring muscles during activities such as kicking, sprinting, stopping, accelerating and tackling, particularly when the hamstring muscles are contracting eccentrically (Arnason et al., 2008, Brooks et al., 2006, Ekstrand et al., 2012, Kumazaki et al., 2012, Opar et al., 2012, Orchard, 2001, Verrall et al., 2001, Woods et al., 2004). The eccentric nature of these movements are considered the most hazardous in terms of sustaining a muscle strain as the movement demands may exceed the mechanical limits of the tissue (Lee et al., 2009, Opar et al., 2012, Thelen et al., 2005a). Risk factors that lead to HSIs can be separated into modifiable risk factors such as; strength imbalances, fatigue and lack of flexibility; as well as non-modifiable risk factors such as; increased age, ethnicity and previous HSIs (Bennell et al., 1998, Brooks et al., 2006, Copland et al., 2009, Croisier et al., 2002, Croisier et al., 2008, Ekstrand et al., 2012, Gabbe et al., 2002, Gabbe et al., 2006a, Heiser et al., 1984, Jonhagen et al., 1994, Opar et al., 2012, Orchard et al., 1997, Orchard, 2001, Sugiura et al., 2008, Verrall et al., 2001, Woods et al., 2004). Considering the different roles that playing positions undertake in cricket and the number of strains occurring for pace bowlers, it is assumed that playing position may play a role in the incidence of HSIs in cricket. Further, skill level would appear to influence the incidence of HSIs as elite level cricket players sustain more strains than junior level cricketers.

In order to prevent HSIs, it is important to determine the most predictive risk factors and develop interventions to address these where possible. Including a concise warm-up before all physical activity is recommended to help prevent injuries but there is limited evidence to support the effectiveness in reducing HSIs (Kujala et al., 1997, Petersen and Hölmich, 2005). Match specific training in a fatigued state has been suggested as a prevention strategy for HSIs, with the belief that athletes would become more aware of muscle movements and become more able to maintain a normal biomechanical gait during match play if they are more conditioned for the tasks (Verrall et al., 2005, Petersen and Hölmich, 2005). However, the most researched and supported prevention strategy for HSIs is the use of eccentric hamstring strength training. Exercises such as the NHE, flywheel training, eccentric backward steps, stiff leg deadlift and single leg deadlifts can all be useful HSI prevention exercises (Arnason et al., 2008, Askling et al., 2003, Brooks et al., 2006, Engebretsen et al., 2008, Gabbe et al., 2006b, Mjøltnes et al., 2004, Opar et al., 2012, Brughelli and Cronin, 2008). The most effective and widespread training technique is the use of the NHE, with HSI reductions of up to 65% in elite soccer and rugby union teams compared to control groups of a previous year with no NHE training (Arnason et al., 2008, Brooks et al., 2006). Some modifications have been suggested to improve the effect of the NHE; using it in conjunction with a full hamstring resistance training program, performing more eccentric exercises at a greater hamstring length and monitoring hamstring strength asymmetries that may exist

between limbs (Arnason et al., 2008, Brughelli and Cronin, 2008, Iga et al., 2012, Opar et al., 2013a).

Compared to traditional free weight strengthening exercises, the NHE is a self-monitored strengthening exercise that provides relatively little feedback for athletes in terms of performance. For example, many athletes are unable to produce sufficient force to slowly lower the body through a full NHE range of motion initially, meaning only advanced athletes are likely to require additional loading in this exercise. An increase in NHE strength is therefore normally demonstrated by the athlete being able to control their movements throughout a larger range of motion in the eccentric phase or by increasing the number of sets and repetitions performed with the initial range of motion.

Psychological strategies that increase the amount of feedback may therefore be useful in the NHE to improve the overall quality of training. Such approaches have demonstrated significant improvements in strength, power and skill-based tasks when associated with complex movements related to sport (Argus et al., 2011, Jung and Hallbeck, 2007, Kim and Kramer, 1997, McNair et al., 1996, Tod et al., 2005). Therefore, psychological strategies may play an integral role in improving eccentric knee flexor strength as well as reducing between limb asymmetries in weaker players who are at increased risk of HSIs. AF such as verbal and visual feedback have been demonstrated to produce small to large effect size improvements in performance across multiple disciplines and therefore its use may be a valuable tool for athlete development (Argus et al., 2011, Jung and Hallbeck, 2007, Keller et al., 2014a, Keller et al., 2014b, Kellis and Baltzopoulos, 1996, Kilduski and Rice, 2003, Kim and Kramer, 1997). Additionally, AF has the potential to help reduce persistent between limb strength asymmetries (Gokeler et al., 2013). Therefore, given information surrounding HSIs in cricket and the potential benefits of AF in improving performance, the two studies of this thesis were conducted in order to:

1. Determine the effect of experience level in cricket and playing position on the extent of bilateral knee flexor strength and between limb knee flexor strength asymmetries through the NHE assessment tool.
2. Determine the effect of real-time knee flexor force feedback on between limb knee flexor strength asymmetries and bilateral knee flexor strength outputs during the performance of the NHE.

It was hypothesised that;

1. Elite level cricket players would present with greater eccentric knee flexor strength and reduced bilateral knee flexor strength asymmetries compared to sub-elite and school level cricket players; with bowlers presenting with the greatest limb asymmetry and the front leg being the stronger limb for all playing positions.

2. Real-time visual feedback during the NHE would reduce between limb knee flexor strength asymmetries and increase knee flexor strength outputs.

Comparisons of Eccentric Knee Flexor Strength and Asymmetries Across Elite, Sub-Elite and School Level Cricket Players

The aim of study one, as presented in chapter three of the thesis was to; (1) determine the effect different player parameters had on eccentric knee flexor strength and between limb strength asymmetries in elite, sub-elite and school level cricket players; as well as (2) determine if playing position and limb role influenced eccentric knee flexor strength or the magnitude of asymmetries. Using a cross sectional comparative study design, 74 male cricket players (16 elite level, 32 sub-elite level and 26 school level) with at least two years of experience playing cricket at their skill level were involved in the study. Data was collected using the NHE assessment tool at the start of pre-season for all teams. Testing consisted of one set of three maximal repetitions of the NHE with 15 seconds inter-repetition rest. Mean peak force for the three repetitions was calculated for each limb and bilateral asymmetries was determined from the differences.

Although there were significant differences in the age and anthropometry of the three skill level groups, there were no significant between group differences in any of the absolute or relative NHE measures. There was however, small to moderate effect size differences for elite and sub-elite players having greater absolute mean peak force outputs compared to school level athletes. Inversely, small to moderate effect size differences were observed for school level players having greater relative mean peak force outputs compared to elite and sub-elite. Additionally, skill level did not significantly influence the magnitude of bilateral limb asymmetries with only small effect sizes demonstrated between all skill levels.

Comparisons between batters and bowlers demonstrated that there were no significant differences between these groups for absolute and relative mean peak force outputs. Bowlers did demonstrate lower relative eccentric knee flexor force outputs compared to batters with a small to moderate effect size difference between these groups.

Effect of Acute Augmented Feedback on Bilateral Limb Asymmetries and Eccentric Knee Flexor Strength During the Nordic Hamstring Exercise

Study two, as presented in chapter four, had a primary aim of determining the acute effects of AF provided during the NHE in reducing bilateral knee flexor strength asymmetries. The secondary aim of the study was to determine whether acute real-time visual feedback provided during the NHE would significantly increase bilateral knee flexor strength outputs. Using a crossover study design, 44 male cricket players were recruited from sub-elite ($n = 23$) and school level ($n = 21$) cricket teams. All participants had at least two years of experience playing in their divisions. Athletes performed two separate testing sessions,

separated by a week, completed at the same time each week at the start of the training week during the start of pre-season training. Testing involved two sets of three maximum repetitions of the NHE separated by 15 seconds inter-repetition rest and four minutes rest between sets on the assessment device following a warm-up set. Consistent with the cross over study design, real-time visual feedback was provided to half of the players in the first session and the other half of the players in the second session. When feedback was provided, athletes were instructed to perform the NHE with the intention to reduce any between limb strength imbalances. Feedback was given in real-time on a computer display in front of the athletes with force outputs for both limbs traced on a graph. Mean peak force for the three repetitions was calculated for each limb and bilateral asymmetries was determined from the differences.

The groups were homogenous in physical characteristics with FB1 group receiving feedback in the first testing session and FB2 group receiving feedback in the second testing session. No significant changes in bilateral limb asymmetries were seen with feedback, although a small to moderate effect size decrease was observed with feedback. However, feedback did significantly increase mean peak force production with moderate effect size differences between the conditions. Further sub-analysis found that the increase in mean peak force was a result of the athletes significantly increasing their weak limb force when feedback was provided.

Discussion

This thesis was performed to contribute to the knowledge of eccentric knee flexor strength in cricket by providing some insight into potential HSI prevention strategies for this sport. Prevention strategies are important as HSIs are occurring with increased frequency in elite level cricket. Specifically, many members of the Australian cricket team in the 2014–2015 season incurred HSIs that resulted in the players missing games. These players included Michael Clarke, Mitchell Johnson, Mitchell Marsh, James Patterson, Shane Watson, Aaron Finch, Nathan Coulter-Nile and Usman Khawaja.

An interesting finding associated with study one was that elite level athletes produced similar absolute eccentric knee flexor force compared to sub-elite and even school level cricket players. A major difference between these skill levels is that elite athletes train more often, at greater intensities and have more frequent matches, yet their absolute eccentric knee flexor strength is similar to sub-elite and school level athletes. Further, the elite players were significantly heavier than the schoolboy players, meaning a tendency for a reduced level of relative eccentric knee flexor strength in the elite players.

When comparing relative force outputs to mass, elite level athletes presented with lower mean peak force outputs even though these athletes are under greater physiological

demands during a competitive season. This may be a reason for why the number of HSIs occurring in elite level cricket is greater than that of junior level cricket. Although non-significant, the small to moderate effect size suggested that bowlers tended to be weaker than batters in terms of relative mean peak force outputs, even though they are the athletes under the greatest amount of hamstring load due to the actions during the bowling phase. This may be one contributing factor to the greater number of HSIs occurring in pace bowlers compared to batters and suggest that pace bowlers need to develop greater eccentric knee flexor strength to help reduce HSI risk. Collectively, these trends for differences in relative strength may contribute to elite pace bowlers having the highest rate of HSIs. This would therefore suggest that elite cricketers (especially pace bowlers) should devote greater emphasis to increasing eccentric knee flexor strength during the pre-season and maintaining strength throughout the competitive season to potentially help to reduce the number of HSIs occurring.

As the front leg may undergo greater loading during pace bowling, throwing and batting, it was also felt important to quantify whether significant differences existed in the eccentric knee flexor strength of both limbs. The lack of any significant difference between front and back limb force outputs was therefore somewhat unexpected. While more research is required, the lack of between limb differences may suggest that an eccentric knee flexor strength training program need not focus on the front vs back leg, rather it should focus on developing strength in both limbs and/or reducing asymmetries between the stronger and weaker limb.

The average between limb asymmetry between the three groups examined in the present study was similar with approximately one third of the athletes with a limb asymmetry of $\geq 15\%$ (31.3%, 34.4% and 30.8% for elite, sub-elite and school level groups, respectively). The degree of asymmetries did not appear to differ between elite, sub-elite and school level cricket players (11.5%, 15.1% and 12.6%, respectively) or between playing positions (13.7% and 13.2% for bowlers and batters respectively). This suggests that the nature of the sport does not appear to result in chronic changes in the degree of limb asymmetries.

As previously mentioned, the transferability of the results measured at the start and end of the pre-season phases for Australian football (Opar et al., 2015a) and rugby union (Bourne et al., 2015b) using the same device is unknown for cricket players. The key point that can be summarised from these two previous football studies is that there is a threshold level of eccentric knee flexor strength and/or bilateral limb asymmetries that is required to reduce the risk of sustaining a HSI. These Australian football and rugby union studies suggest that once the players become stronger than this threshold, bilateral limb asymmetries may play a greater role in the risk of developing HSIs. Therefore, a systematic approach to eccentric knee flexor strength training which focuses on increasing eccentric

knee flexor strength and reducing bilateral asymmetries would appear to have the greatest success in helping to reduce the risk of HSIs in cricket.

By targeting one of the most supported HSI prevention strategies; increasing eccentric knee flexor strength and further supporting this by reducing eccentric knee flexor strength asymmetries, there appears to be considerable potential to limit the number of HSIs occurring in elite cricket. Therefore, the development of more effective eccentric hamstring strengthening protocols is required.

Study two of this thesis presents supportive evidence to suggest that the use of real-time visual feedback during the NHE can result in significant acute increases in eccentric knee flexor strength and small effect size decreases in between limb strength asymmetries. Consequently, the chronic utilisation of real-time visual feedback may be a valuable tool for cricket players to help address the strength weaknesses in pace bowlers and elite level players and further address any limb asymmetries that may be present. The primary aim of study two was to decrease between limb eccentric knee flexor strength asymmetries but it was found that there were no significant reductions in this outcome when feedback was applied. However, the small effect size trend that was noted for changes in eccentric knee flexor strength asymmetries and the increase in force output for the weaker limb (moderate effect size) suggests that there is potential for the chronic use of real-time visual feedback to reduce limb asymmetries by preferentially increasing the strength of the weaker limb. Athletes were instructed to focus on reducing any between limb strength imbalances as much as possible when feedback was provided and a consequence of this was an increase in force production during feedback conditions.

The relative effectiveness of the feedback approach may also be examined by altering the task goal provided to the athletes. For example, if the athletes are specifically directed to increase their maximum force production during the NHE as well as focusing on reducing any between limb strength asymmetries, there is potential for this to result in greater acute force production in each training session and therefore larger increases in eccentric strength and reductions in the between limb strength asymmetries over the course of a typical training cycle.

In summary, elite level athlete's absolute eccentric knee flexor strength is similar to sub-elite and school level cricket players when it should be greater considering the elite players' greater body mass, absolute running workloads and higher number of HSIs. Real-time visual feedback during the NHE can be a valuable tool in increasing the acute force outputs which may accelerate strength gains and reductions of between limb strength asymmetries over the course of a typical training cycle. The challenge is now determining what eccentric knee flexor strength threshold best predicts HSIs in cricket. Once this is known, strength and

conditioning staff may focus on their weaker players reaching this threshold, and once that is achieved direct more focus to reducing between limb strength asymmetries.

Practical Applications

The literature reviewed in this thesis provided evidence for the primary risk factors influencing HSI risk in cricket and some potential intervention strategies for the development of effective HSI prevention strategies. Eccentric hamstring strength training is the most effective HSI prevention protocol available for many high-intensity sports (Arnason et al., 2008, Askling et al., 2003, Brooks et al., 2006, Engebretsen et al., 2008, Gabbe et al., 2006b, Mjølshes et al., 2004, Opar et al., 2012). When eccentric hamstring strength training is incorporated into a well-structured strength and conditioning program and athlete management system it can help to reduce the risk of HSIs substantially (Arnason et al., 2008, Brooks et al., 2006). The data presented in this thesis provide preliminary data for eccentric knee flexor strength and strength asymmetries in elite, sub-elite and school level athletes. Additionally, the data provide support for AF strategies that may be able to further enhance eccentric knee flexor strength gains and reduce between limb asymmetries during the NHE.

Based on the findings in the present thesis, several practical applications for athletes and coaching staff to consider are suggested in order to better develop eccentric knee flexor strength in cricket players and ultimately reduce HSI risk:

- 1) Elite level athletes require a well-structured pre-season training program (incorporating the NHE, along with other eccentric knee flexor exercises) to increase eccentric knee flexor strength in order to be able to combat the large forces applied to the body during the competitive season.
- 2) Once elite level athletes have obtained an as yet unidentified eccentric knee flexor force threshold, this should be maintained and focus should be on reducing any between limb strength asymmetries.
- 3) Where possible, feedback is a valuable tool for coaching staff to provide their athletes during eccentric knee flexor strength training to help increase acute force production, especially within the weaker limb.
- 4) Although the HSI rate is lower in junior than elite level cricket, the inclusion of the NHE (or other eccentric hamstring exercises) in the training program of junior players may be important, as it would allow them to develop a sound fundamental strength level as they progress through skill levels and inevitably progress into more demanding training and match formats.

- 5) The greatest need for increased eccentric knee flexor strength is with elite level pace bowlers as they are the most at risk of sustaining a HSI and have presented with the lowest relative force outputs. Therefore, eccentric knee flexor strengthening exercises may be a greater priority in bowler's strength training sessions.

Limitations

The authors note the following as limitations to the two research studies:

- 1) A larger sample size per skill level in study one may have helped to develop a normative database for eccentric knee flexor strength and eccentric knee flexor strength asymmetries that would provide useful information to other cricket teams.
- 2) A larger sample size of elite level athletes in study one to match that of sub-elite and school level may have added to the generalisability of this data and its potential use in a normative database. However, this was not possible as only one elite team exists per state.
- 3) Testing at the start and end of pre-season training in study one may have allowed for further inference of the strength differences between skill levels at the beginning of the competitive season.
- 4) A more homogeneous group with one skill level of the same sport may have increased the probability that study two could demonstrate a significant difference in the ability for AF to reduce between limb eccentric knee flexor asymmetries
- 5) The inclusion of elite level athletes in the sample for study two may have provided greater transferability in the true magnitude of the effect of AF for that skill level.

Directions for Future Research

This current thesis has made an original contribution to our knowledge and understanding of eccentric hamstring strength across multiple skill levels in cricket and the effect of AF to reduce between limb strength asymmetries and increase eccentric knee flexor strength. To gain further understanding of the effect of prevention strategies such as the NHE and the use of AF, further research is required addressing some of the following areas:

- 1) Collecting greater amounts of normative data for elite, sub-elite and school level cricket players of both genders.
- 2) A longitudinal study tracking eccentric knee flexor strength from the start of pre-season and continuing throughout an entire competitive season for elite, sub-elite

and school level cricket players. From this, a HSI risk ratio based on eccentric knee flexor strength and between limb asymmetries at the start and end of pre-season training would be able to be calculated, similar to previous studies in Australian football and rugby union (Bourne et al., 2015b, Opar et al., 2015a).

- 3) A longitudinal study involving multiple elite level teams with the use of augmented real-time visual feedback during the NHE for an entire pre-season period would provide greater insight into the potential chronic effects of using feedback. The associated changes throughout a competitive season should then be followed with some teams receiving and other teams not receiving feedback to assess the chronic effect of feedback on eccentric knee flexor strength indices and HSI rates.
- 4) Given the lack of information available, injury epidemiology studies are required for sub-elite level cricket players.

References

- ANASTASI, S. M. & HAMZEH, M. A. 2011. Does the eccentric Nordic Hamstring exercise have an effect on isokinetic muscle strength imbalance and dynamic jumping performance in female rugby union players? *Isokinetics & Exercise Science*, 19, 251-260.
- ARGUS, C. K., GILL, N. D., KEOGH, J. W. & HOPKINS, W. G. 2011. Acute effects of verbal feedback on upper-body performance in elite athletes. *Journal of Strength and Conditioning Research*, 25, 3282-7.
- ARNASON, A., ANDERSEN, T. E., HOLME, I., ENGBRETSSEN, L. & BAHR, R. 2008. Prevention of hamstring strains in elite soccer: an intervention study. *Scandinavian Journal of Medicine & Science in Sports*, 18, 40-48.
- ARNASON, A., SIGURDSSON, S. B., GUDMUNDSSON, A., HOLME, I., ENGBRETSSEN, L. & BAHR, R. 2004. Risk Factors for Injuries in Football. *The American Journal of Sports Medicine*, 32, 5S-16S.
- ASKLING, C., KARLSSON, J. & THORSTENSSON, A. 2003. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scandinavian Journal of Medicine & Science in Sports*, 13, 244-50.
- ASKLING, C. M., TENGVAR, M., SAARTOK, T. & THORSTENSSON, A. 2008. Proximal Hamstring Strains of Stretching Type in Different Sports: Injury Situations, Clinical and Magnetic Resonance Imaging Characteristics, and Return to Sport. *The American Journal of Sports Medicine*, 36, 1799-1804.
- BENNEL, K., WAJSWELNER, H., LEW, P., SCHALL-RIAUCOUR, A., LESLIE, S., PLANT, D. & CIRONE, J. 1998. Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. *British Journal of Sports Medicine*, 32, 309-14.
- BOURNE, M. N., OPAR, D. A., WILLIAMS, M. D., AL NAJJAR, A. & SHIELD, A. J. 2015a. Muscle activation patterns in the Nordic hamstring exercise: Impact of prior strain injury. *Scandinavian Journal of Medicine & Science in Sports*.
- BOURNE, M. N., OPAR, D. A., WILLIAMS, M. D. & SHIELD, A. J. 2015b. Eccentric Knee Flexor Strength and Risk of Hamstring Injuries in Rugby Union: A Prospective Study. *The American Journal Sports Medicine*, 43, 2663-70.
- BRAHAM, R., FINCH, C. F., MCINTOSH, A. & MCCRORY, P. 2004. Community level Australian Football: a profile of injuries. *Journal of Science and Medicine in Sport*, 7, 96-105.
- BRIAN, C., CARL, G. M. & IRIS, F. K. 2000. Effect of visual feedback and verbal encouragement on concentric quadriceps and hamstrings peak torque of males and females. *Isokinetics & Exercise Science*, 8, 1.

- BROCKETT, C. L., MORGAN, D. L. & PROSKE, U. 2001. Human hamstring muscles adapt to eccentric exercise by changing optimum length. *Medicine and Science in Sports and Exercise*, 33, 783-90.
- BROOKS, J. H. M., FULLER, C. W., KEMP, S. P. T. & REDDIN, D. B. 2006. Incidence, Risk, and Prevention of Hamstring Muscle Injuries in Professional Rugby Union. *The American Journal of Sports Medicine*, 34, 1297-1306.
- BRUGHELLI, M. & CRONIN, J. 2008. Preventing Hamstring Injuries in Sport. *Strength & Conditioning Journal*, 30, 55-64 10.1519/SSC.0b013e3181638263.
- CANNONIER, C., PANDA, B. & SARANGI, S. 2013. 20-Over Versus 50-Over Cricket: Is There a Difference? *Journal of Sports Economics*, 16, 760-783.
- CHUMANOV, E. S., HEIDERSCHEIT, B. C. & THELEN, D. G. 2007. The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. *Journal of Biomechanics*, 40, 3555-62.
- CHUMANOV, E. S., HEIDERSCHEIT, B. C. & THELEN, D. G. 2011. Hamstring musculotendon dynamics during stance and swing phases of high-speed running. *Medicine and Science in Sports and Exercise*, 43, 525-32.
- CLARK, R., BRYANT, A., CULGAN, J.-P. & HARTLEY, B. 2005. The effects of eccentric hamstring strength training on dynamic jumping performance and isokinetic strength parameters: a pilot study on the implications for the prevention of hamstring injuries. *Physical Therapy in Sport*, 6, 67-73.
- COHEN, J. 1988. Statistical Power Analysis for the Behavioral Sciences. 2nd edn. Hillsdale, New Jersey: L. Erlbaum.
- CONCHOLA, E. C., THOMPSON, B. J. & SMITH, D. B. 2013. Effects of neuromuscular fatigue on the electromechanical delay of the leg extensors and flexors in young and old men. *European Journal of Applied Physiology*, 113, 2391-9.
- COPLAND, S. T., TIPTON, J. S. & FIELDS, K. B. 2009. Evidence-Based Treatment of Hamstring Tears. *Curr Sports Med Rep*, 8, 308-314.
- CROISIER, J. L. 2004. Factors associated with recurrent hamstring injuries. *Sports Medicine*, 34, 681-95.
- CROISIER, J. L., FORTHOMME, B., NAMUROIS, M. H., VANDERTHOMMEN, M. & CRIELAARD, J. M. 2002. Hamstring muscle strain recurrence and strength performance disorders. *The American Journal of Sports Medicine*, 30, 199-203.
- CROISIER, J. L., GANTEAUME, S., BINET, J., GENTY, M. & FERRET, J. M. 2008. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *The American Journal of Sports Medicine*, 36, 1469-75.

- CRONIN, J. B., BRESSEL, E. & FINN, L. 2008. Augmented Feedback Reduces Ground Reaction Forces in the Landing Phase of the Volleyball Spike Jump. *Journal of Sport Rehabilitation*, 17, 148-159.
- CROSS, K. M., GURKA, K. K., CONAWAY, M. & INGERSOLL, C. D. 2010. Hamstring Strain Incidence Between Genders and Sports in NCAA Athletics. *Athletic Training & Sports Health Care: The Journal for the Practicing Clinician*, 2, 124-130.
- DENNIS, R. J., FINCH, C. F. & FARHART, P. J. 2005. Is bowling workload a risk factor for injury to Australian junior cricket fast bowlers? *British Journal of Sports Medicine*, 39, 843-846.
- DRAKE, R. L., VOGL, W., MITCHELL, A. & GRAY, H. 2010. *Gray's anatomy for students*, Philadelphia, Churchill Livingstone/Elsevier.
- EKSTRAND, J., HEALY, J. C., WALDÉN, M., LEE, J. C., ENGLISH, B. & HÄGGLUND, M. 2012. Hamstring muscle injuries in professional football: the correlation of MRI findings with return to play. *British Journal of Sports Medicine*, 46, 112-117.
- ENGEBRETSEN, A. H., MYKLEBUST, G., HOLME, I., ENGBRETSSEN, L. & BAHR, R. 2008. Prevention of injuries among male soccer players: a prospective, randomized intervention study targeting players with previous injuries or reduced function. *The American Journal of Sports Medicine*, 36, 1052-60.
- FINCH, C. F., WHITE, P., DENNIS, R., TWOMEY, D. & HAYEN, A. 2010. Fielders and batters are injured too: a prospective cohort study of injuries in junior club cricket. *Journal of Science and Medicine in Sport*, 13, 489-95.
- FROST, W. L. & CHALMERS, D. J. 2014. Injury in elite New Zealand cricketers 2002-2008: descriptive epidemiology. *British Journal of Sports Medicine*, 48, 1002-7.
- FYFE, J. J., OPAR, D. A., WILLIAMS, M. D. & SHIELD, A. J. 2013. The role of neuromuscular inhibition in hamstring strain injury recurrence. *Journal of Electromyography and Kinesiology*, 23, 523-30.
- GABBE, B., FINCH, C., WAJSWELNER, H. & BENNELL, K. 2002. Australian football: injury profile at the community level. *Journal of Science and Medicine in Sport*, 5, 149-60.
- GABBE, B. J., BENNELL, K. L. & FINCH, C. F. 2006a. Why are older Australian football players at greater risk of hamstring injury? *Journal of Science and Medicine in Sport*, 9, 327-33.
- GABBE, B. J., BRANSON, R. & BENNELL, K. L. 2006b. A pilot randomised controlled trial of eccentric exercise to prevent hamstring injuries in community-level Australian Football. *Journal of Science and Medicine in Sport*, 9, 103-9.
- GARRETT, W. E., JR. 1996. Muscle strain injuries. *The American Journal of Sports Medicine*, 24, S2-8.

- GOKELER, A., BENJAMINSE, A., HEWETT, T., PATERNO, M., FORD, K., OTTEN, E. & MYER, G. 2013. Feedback Techniques to Target Functional Deficits Following Anterior Cruciate Ligament Reconstruction: Implications for Motor Control and Reduction of Second Injury Risk. *Sports Medicine*, 43, 1065-1074.
- GOODE, A. P., REIMAN, M. P., HARRIS, L., DELISA, L., KAUFFMAN, A., BELTRAMO, D., POOLE, C., LEDBETTER, L. & TAYLOR, A. B. 2015. Eccentric training for prevention of hamstring injuries may depend on intervention compliance: a systematic review and meta-analysis. *British Journal of Sports Medicine*, 49, 349-356.
- HEIDERSCHEIT, B. C., HOERTH, D. M., CHUMANOV, E. S., SWANSON, S. C., THELEN, B. J. & THELEN, D. G. 2005. Identifying the time of occurrence of a hamstring strain injury during treadmill running: a case study. *Clinical Biomechanics*, 20, 1072-8.
- HEISER, T. M., WEBER, J., SULLIVAN, G., CLARE, P. & JACOBS, R. R. 1984. Prophylaxis and management of hamstring muscle injuries in intercollegiate football players. *The American Journal of Sports Medicine*, 12, 368-70.
- HICKEY, J., SHIELD, A. J., WILLIAMS, M. D. & OPAR, D. A. 2013. The financial cost of hamstring strain injuries in the Australian Football League. *British Journal of Sports Medicine*.
- HOUGHTON, L., DAWSON, B., RUBENSON, J. & TOBIN, M. 2011. Movement patterns and physical strain during a novel, simulated cricket batting innings (BATEX). *Journal of Sports Sciences*, 29, 801-809.
- HRYDOMALLIS, C. 2013. Injury Incidence, Risk Factors and Prevention in Australian Rules Football. *Sports Medicine*, 43, 339-354.
- IGA, J., FRUER, C. S., DEIGHAN, M., CROIX, M. D. & JAMES, D. V. 2012. 'Nordic' hamstrings exercise - engagement characteristics and training responses. *International Journal of Sports Medicine*, 33, 1000-4.
- IMPELLIZZERI, F. M., BIZZINI, M., RAMPININI, E., CEREDA, F. & MAFFIULETTI, N. A. 2008. Reliability of isokinetic strength imbalance ratios measured using the Cybex NORM dynamometer. *Clin Physiol Funct Imaging*, 28, 113-9.
- JOHNSON, J. N. 2003. Competitive swimming illness and injury: common conditions limiting participation. *Curr Sports Med Rep*, 2, 267-71.
- JONHAGEN, S., NEMETH, G. & ERIKSSON, E. 1994. Hamstring injuries in sprinters. The role of concentric and eccentric hamstring muscle strength and flexibility. *The American Journal of Sports Medicine*, 22, 262-6.
- JUNG, M.-C. & HALLBECK, M. S. 2007. Quantification of the effects of instruction type, verbal encouragement, and visual feedback on static and peak handgrip strength. *International Journal of Industrial Ergonomics*, 34, 367-374.

- KELLER, M., LAUBER, B., GEHRING, D., LEUKEL, C. & TAUBE, W. 2014a. Jump performance and augmented feedback: Immediate benefits and long-term training effects. *Human Movement Science*, 36, 177-189.
- KELLER, M., LAUBER, B., GOTTSCHALK, M. & TAUBE, W. 2014b. Enhanced jump performance when providing augmented feedback compared to an external or internal focus of attention. *Journal of Sports Sciences*, 33, 1067-1075.
- KELLIS, E. & BALZPOPOULOS, V. 1996. Resistive eccentric exercise: effects of visual feedback on maximum moment of knee extensors and flexors. *Journal of Orthopaedic & Sports Physical Therapy*, 23, 120-4.
- KILDUSKI, N. C. & RICE, M. S. 2003. Qualitative and Quantitative Knowledge of Results: Effects on Motor Learning. *The American Journal of Occupational Therapy*, 57, 329-336.
- KIM, H. J. & KRAMER, J. F. 1997. Effectiveness of visual feedback during isokinetic exercise. *Journal of Orthopaedic & Sports Physical Therapy*, 26, 318-323.
- KUJALA, U. M., ORAVA, S. & JARVINEN, M. 1997. Hamstring injuries. Current trends in treatment and prevention. *Sports Medicine*, 23, 397-404.
- KUMAZAKI, T., EHARA, Y. & SAKAI, T. 2012. Anatomy and Physiology of Hamstring Injury. *International Journal of Sports Medicine*, 33, 950-954.
- LEARY, T. & WHITE, J. A. 2000. Acute injury incidence in professional county club cricket players (1985-1995). *British Journal of Sports Medicine*, 34, 145-147.
- LEE, M. J., REID, S. L., ELLIOTT, B. C. & LLOYD, D. G. 2009. Running biomechanics and lower limb strength associated with prior hamstring injury. *Medicine and Science in Sports and Exercise*, 41, 1942-51.
- MAIR, S. D., SEABER, A. V., GLISSON, R. R. & GARRETT, W. E., JR. 1996. The role of fatigue in susceptibility to acute muscle strain injury. *The American Journal of Sports Medicine*, 24, 137-43.
- MANSINGH, A., HARPER, L., HEADLEY, S., KING-MOWATT, J. & MANSINGH, G. 2006. Injuries in West Indies cricket 2003-2004. *British Journal of Sports Medicine*, 40, 119-123.
- MCALLISTER, M. J., HAMMOND, K. G., SCHILLING, B. K., FERRERIA, L. C., REED, J. P. & WEISS, L. W. 2014. Muscle activation during various hamstring exercises. *Journal of Strength and Conditioning Research*, 28, 1573-1580.
- MCNAIR, P. J., DEPLEDGE, J., BRETTKELLY, M. & STANLEY, S. N. 1996. Verbal encouragement: effects on maximum effort voluntary muscle action. *British Journal of Sports Medicine*, 30, 243-5.
- MELLION, M. B. 1991. Common cycling injuries. Management and prevention. *Sports Medicine*, 11, 52-70.

- MJØLSNES, R., ARNASON, A., ØSTHAGEN, T., RAASTAD, T. & BAHR, R. 2004. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scandinavian Journal of Medicine & Science in Sports*, 14, 311-317.
- NOVACHECK, T. F. 1998. The biomechanics of running. *Gait Posture*, 7, 77-95.
- NUTTRIDGE, G. A. & MILBURN, P. D. 2004. Cricket injuries: The nature and prevalence of injury in pace bowlers. *New Zealand Journal of Sports Medicine*, 32, 60-68.
- ONO, T., HIGASHIHARA, A. & FUKUBAYASHI, T. 2010a. Hamstring Functions During Hip Extension Exercise Assessed With Electromyography and Magnetic Resonance Imaging. *Research in Sports Medicine*, 19, 42-52.
- ONO, T., OKUWAKI, T. & FUKUBAYASHI, T. 2010b. Differences in activation patterns of knee flexor muscles during concentric and eccentric exercises. *Research in Sports Medicine*, 18, 188-98.
- OPAR, D. A., PIATKOWSKI, T., WILLIAMS, M. D. & SHIELD, A. J. 2013a. A Novel Device Using the Nordic Hamstring Exercise to Assess Eccentric Knee Flexors Strength: A Reliability and Retrospective Injury Study. *Journal of Orthopaedic & Sports Physical Therapy*, 43, 636-40.
- OPAR, D. A., WILLIAMS, M. D. & SHIELD, A. J. 2012. Hamstring strain injuries: factors that lead to injury and re-injury. *Sports Medicine*, 42, 209-26.
- OPAR, D. A., WILLIAMS, M. D., TIMMINS, R. G., DEAR, N. M. & SHIELD, A. J. 2013b. Knee flexor strength and bicep femoris electromyographical activity is lower in previously strained hamstrings. *Journal of Electromyography and Kinesiology*, 23, 696-703.
- OPAR, D. A., WILLIAMS, M. D., TIMMINS, R. G., DEAR, N. M. & SHIELD, A. J. 2013c. Rate of torque and electromyographic development during anticipated eccentric contraction is lower in previously strained hamstrings. *The American Journal of Sports Medicine*, 41, 116-25.
- OPAR, D. A., WILLIAMS, M. D., TIMMINS, R. G., HICKEY, J., DUHIG, S. J. & SHIELD, A. J. 2015a. Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Medicine and Science in Sports and Exercise*, 47, 857-65.
- OPAR, D. A., WILLIAMS, M. D., TIMMINS, R. G., HICKEY, J., DUHIG, S. J. & SHIELD, A. J. 2015b. The Effect of Previous Hamstring Strain Injuries on the Change in Eccentric Hamstring Strength During Preseason Training in Elite Australian Footballers. *The American Journal of Sports Medicine*, 43, 377-384.
- ORCHARD, J., JAMES, T., ALCOTT, E., CARTER, S. & FARHART, P. 2002. Injuries in Australian cricket at first class level 1995/1996 to 2000/2001. *British Journal of Sports Medicine*, 36, 270-274.

- ORCHARD, J., JAMES, T., KOUNTOURIS, A., BLANCH, P., SIMS, K. & ORCHARD, J. 2011. Injury Report 2011: Cricket Australia. *Sport Health*, 29, 16-29.
- ORCHARD, J., JAMES, T., KOUNTOURIS, A. & PORTUS, M. 2010. Changes to injury profile (and recommended cricket injury definitions) based on the increased frequency of Twenty20 cricket matches. *Open Access Journal of Sports Medicine*, 1, 63-76.
- ORCHARD, J., MARSDEN, J., LORD, S. & GARLICK, D. 1997. Preseason Hamstring Muscle Weakness Associated with Hamstring Muscle Injury in Australian Footballers. *The American Journal of Sports Medicine*, 25, 81-85.
- ORCHARD, J. W. 2001. Intrinsic and Extrinsic Risk Factors for Muscle Strains in Australian Football Neither the author nor the related institution has received any financial benefit from research in this study. *The American Journal of Sports Medicine*, 29, 300-303.
- ORCHARD, J. W., JAMES, T. & PORTUS, M. R. 2006. Injuries to elite male cricketers in Australia over a 10-year period. *Journal of Science and Medicine in Sport*, 9, 459-467.
- ORCHARD, J. W., NEWMAN, D., STRETCH, R., FROST, W., MANSINGH, A. & LEIPUS, A. 2005. Methods for injury surveillance in international cricket. *British Journal of Sports Medicine*, 39, e22.
- PETERSEN, C. J., PYNE, D., DAWSON, B., PORTUS, M. & KELLETT, A. 2010. Movement patterns in cricket vary by both position and game format. *Journal of Sports Sciences*, 28, 45-52.
- PETERSEN, J. & HÖLMICH, P. 2005. Evidence based prevention of hamstring injuries in sport. *British Journal of Sports Medicine*, 39, 319-323.
- PETERSEN, J., THORBORG, K., NIELSEN, M. B., BUDTZ-JORGENSEN, E. & HOLMICH, P. 2011. Preventive effect of eccentric training on acute hamstring injuries in men's soccer: a cluster-randomized controlled trial. *The American Journal of Sports Medicine*, 39, 2296-303.
- PHILLIPS, E., FARROW, D., BALL, K. & HELMER, R. 2013. Harnessing and Understanding Feedback Technology in Applied Settings. *Sports Medicine*, 43, 919-925.
- PRIOR, M., GUERIN, M. & GRIMMER, K. 2009. An evidence-based approach to hamstring strain injury: a systematic review of the literature. *Sports Health*, 1, 154-64.
- RANDELL, A. D., CRONIN, J. B., KEOGH, J. W., GILL, N. D. & PEDERSEN, M. C. 2011. Effect of instantaneous performance feedback during 6 weeks of velocity-based resistance training on sport-specific performance tests. *Journal of Strength and Conditioning Research*, 25, 87-93.
- RUMFORD, C. 2011. Twenty20, global disembedding, and the rise of the 'portfolio player'. *Sport in Society*, 14, 1358-1368.

- SCHACHE, A. G., WRIGLEY, T. V., BAKER, R. & PANDY, M. G. 2009. Biomechanical response to hamstring muscle strain injury. *Gait Posture*, 29, 332-8.
- SCHMITT, B., TYLER, T. & MCHUGH, M. 2012. Hamstring injury rehabilitation and prevention of reinjury using lengthened state eccentric training: a new concept. *International Journal of Sports Physical Therapy*, 7, 333-341.
- SCHUERMANS, J., VAN TIGGELEN, D., DANNEELS, L. & WITVROUW, E. 2014. Biceps femoris and semitendinosus—teammates or competitors? New insights into hamstring injury mechanisms in male football players: a muscle functional MRI study. *British Journal of Sports Medicine*, 48, 1599-1606.
- SILDER, A., HEIDERSCHEIT, B. C., THELEN, D. G., ENRIGHT, T. & TUIE, M. J. 2008. MR observations of long-term musculotendon remodeling following a hamstring strain injury. *Skeletal Radiology*, 37, 1101-9.
- SMALL, K., MCNAUGHTON, L. R., GREIG, M., LOHKAMP, M. & LOVELL, R. 2009. Soccer fatigue, sprinting and hamstring injury risk. *International Journal of Sports Medicine*, 30, 573-8.
- SOLE, G., MILOSAVLJEVIC, S., NICHOLSON, H. & SULLIVAN, S. J. 2012. Altered muscle activation following hamstring injuries. *British Journal of Sports Medicine*, 46, 118-123.
- STRETCH, R. A. 2001. Epidemiology of Cricket Injuries. *International SportMed Journal*, 2, 1.
- STRETCH, R. A. 2003. Cricket injuries: a longitudinal study of the nature of injuries to South African cricketers. *British Journal of Sports Medicine*, 37, 250-253.
- SUGIURA, Y., SAITO, T., SAKURABA, K., SAKUMA, K. & SUZUKI, E. 2008. Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. *Journal of Orthopaedic & Sports Physical Therapy*, 38, 457-64.
- THELEN, D. G., CHUMANOV, E. S., BEST, T. M., SWANSON, S. C. & HEIDERSCHEIT, B. C. 2005a. Simulation of biceps femoris musculotendon mechanics during the swing phase of sprinting. *Medicine and Science in Sports and Exercise*, 37, 1931-8.
- THELEN, D. G., CHUMANOV, E. S., HOERTH, D. M., BEST, T. M., SWANSON, S. C., LI, L., YOUNG, M. & HEIDERSCHEIT, B. C. 2005b. Hamstring muscle kinematics during treadmill sprinting. *Medicine and Science in Sports and Exercise*, 37, 108-14.
- TIMMINS, R. G., BOURNE, M. N., SHIELD, A. J., WILLIAMS, M. D., LORENZEN, C. & OPAR, D. A. 2015. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. *British Journal of Sports Medicine*.
- TIMMINS, R. G., OPAR, D. A., WILLIAMS, M. D., SCHACHE, A. G., DEAR, N. M. & SHIELD, A. J. 2014. Reduced biceps femoris myoelectrical activity influences eccentric knee

- flexor weakness after repeat sprint running. *Scandinavian Journal of Medicine & Science in Sports*, 24, e299-305.
- TOD, D. A., IREDALE, K. F., MCGUIGAN, M. R., STRANGE, D. E. & GILL, N. 2005. "Psyching-up" enhances force production during the bench press exercise. *Journal of Strength and Conditioning Research*, 19, 599-603.
- VAN DER HORST, N., SMITS, D.-W., PETERSEN, J., GOEDHART, E. A. & BACKX, F. J. G. 2015. The Preventive Effect of the Nordic Hamstring Exercise on Hamstring Injuries in Amateur Soccer Players: A Randomized Controlled Trial. *The American Journal of Sports Medicine*, 43, 1316-1323.
- VERRALL, G. M., KALAIRAJAH, Y., SLAVOTINEK, J. P. & SPRIGGINS, A. J. 2006. Assessment of player performance following return to sport after hamstring muscle strain injury. *Journal of Science and Medicine in Sport*, 9, 87-90.
- VERRALL, G. M., SLAVOTINEK, J. P. & BARNES, P. G. 2005. The effect of sports specific training on reducing the incidence of hamstring injuries in professional Australian Rules football players. *British Journal of Sports Medicine*, 39, 363-8.
- VERRALL, G. M., SLAVOTINEK, J. P., BARNES, P. G., FON, G. T. & SPRIGGINS, A. J. 2001. Clinical risk factors for hamstring muscle strain injury: a prospective study with correlation of injury by magnetic resonance imaging. *British Journal of Sports Medicine*, 35, 435-440.
- WITVROUW, E., MAHIEU, N., DANNEELS, L. & MCNAIR, P. 2004. Stretching and injury prevention: an obscure relationship. *Sports Medicine*, 34, 443-9.
- WOODS, C., HAWKINS, R. D., MALTBY, S., HULSE, M., THOMAS, A. & HODSON, A. 2004. The Football Association Medical Research Programme: an audit of injuries in professional football--analysis of hamstring injuries. *British Journal of Sports Medicine*, 38, 36-41.
- WORRELL, T. W., PERRIN, D. H., GANSNEDER, B. M. & GIECK, J. H. 1991. Comparison of isokinetic strength and flexibility measures between hamstring injured and noninjured athletes. *Journal of Orthopaedic & Sports Physical Therapy*, 13, 118-25.
- WULF, G., SHEA, C. & LEWTHWAITE, R. 2010. Motor skill learning and performance: a review of influential factors. *Medical Education*, 44, 75-84.
- YU, B., QUEEN, R. M., ABBEY, A. N., LIU, Y., MOORMAN, C. T. & GARRETT, W. E. 2008. Hamstring muscle kinematics and activation during overground sprinting. *Journal of Biomechanics*, 41, 3121-6.

Appendices

Appendix A: Informed Consent Form

CONSENT FORM

BUHREC Protocol Number: RO1824

STUDY TITLE: Differences in Eccentric Hamstring Strength and Asymmetries Across Elite, Sub-elite and School Level Cricket Players

PRINCIPLE INVESTIGATORS:

Dr Justin Keogh

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ABN 88 010 694 121
CRICOS CODE 00017B

By signing below, I confirm that I have read and understand the information provided to me in particular I have noted that:

- I have read the explanatory statement for the research project “Differences in eccentric hamstring strength and asymmetries across elite, sub-elite and school level cricket players” and clearly understand the content, and what is being asked of me as a volunteer in the study.
- Any questions that I have had have been answered to my satisfaction. I also understand that I can ask questions about the study and my participation at any time.
- The risks associated with my participation in the study have been clearly explained to me and I clearly understand the risks involved in my participation.

- I understand that my participation in this research is voluntary and I am able to withdraw from the study at any time without penalty, guilt or aggravation from the investigators and coaching staff.
- I understand the potential benefits involved with my participation in study.
- I understand all results obtained in this project will remain confidential and that my name will not be published with my results.
- I understand that coaching staff may request my results to help to improve my performance as a player and that it will have no influence on player selection.
- I understand that at the appropriate time I will receive feedback on my performance in the project and that I may request my results at the end of the study.
- I understand that the project will be carried out as described in the explanatory statement, a copy of which I have retained.
- I understand that this project will meet the National Statement on Ethical Conduct in Human Research (Privacy)
- I give my consent to participate in the study “Differences in eccentric hamstring strength and asymmetries across elite, sub-elite and school level cricket players”.

Please tick the appropriate boxes if you give consent for the following two exchanges of your personal data to occur:

- ☐ I am happy for the information that is gathered as a result of the study to be viewed by the coaching and medical staff of my cricket team;
- ☐ I am happy for my hamstring injury history (if relevant) to be accessed by the researchers. .

Signatures: Participant Full Name Signature/...../..... Date
..... Parent / Guardian (if under 18) Signature/...../..... Date
Wade Chalker Investigator Signature/...../..... Date

Appendix B: Participation Information Form – Study 1

EXPLANATORY STATEMENT

BUHREC Protocol Number: RO1824

STUDY TITLE: Differences in Eccentric Hamstring Strength and Asymmetries Across Elite, sub-elite and School Level Cricket Players

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Wade Chalker

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Dr Anthony Shield

Queensland University of Technology
07 3138 5829

Dr David Opar

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Who is doing the study?

Hamstring strains are becoming a more common injury in sports including cricket. Researchers from Bond University are conducting this study to evaluate the symmetry of hamstring strength in cricket players of different standards. The results from the study may be used by the coaching staff and strength and conditioning staff of each team to improve player development.

Why are we doing the study?

We are conducting the following study as there is limited research based on strength in hamstring muscles for cricket players as hamstring strains are amongst the highest occurring injuries in cricket. This research will help to identify asymmetries or deficits in hamstring strength which may lead to an increased risk of hamstring injury.

Your involvement in the study

If you choose to participate in the study, you will be asked to attend two testing sessions during training for your team. Each session will require ~10 minutes of your time to collect enough data. There will be an explanation session where you will observe a demonstration about the testing protocol, partake in a familiarisation session on the testing device, complete an informed consent document, have any questions that you may have answered and complete some basic measurements such as height and weight. A previous injury report may be required for your team's physiotherapist, medical staff or yourself to complete.

Testing will occur one week prior to the familiarisation at the start of regular training. Each time you perform the test you will perform a standardized warm-up and then perform one maximal set of three repetitions on the testing device. In total, you will be involved in two sessions over two weeks.

Testing will require you to perform a Nordic hamstring exercise on a device that will measure your force output of both left and right legs.

Nordic hamstring exercise testing

During the testing day, you will be required to wear comfortable clothing and footwear appropriate for performing maximal strength testing.

Each testing session will consist of you performing a submaximal warm-up set of three repetitions on the device followed by one set of three repetitions with 15 seconds rest between repetitions. Each set will be separated by four minutes rest.

The Nordic hamstring exercise will be performed on the testing device seen in Figure 1. Force gauges are attached to your ankle during the movement to measure the force output of each hamstring muscle group.

You will need to perform the Nordic hamstring exercise with the following movement requirements:

- Gradually lean forward at the slowest possible speed
- Maximally resist the forward moving motion with both limbs
- Hold your trunk and hips in a neutral position throughout the manoeuvre
- Keep hands across your chest until you have lost control of movement

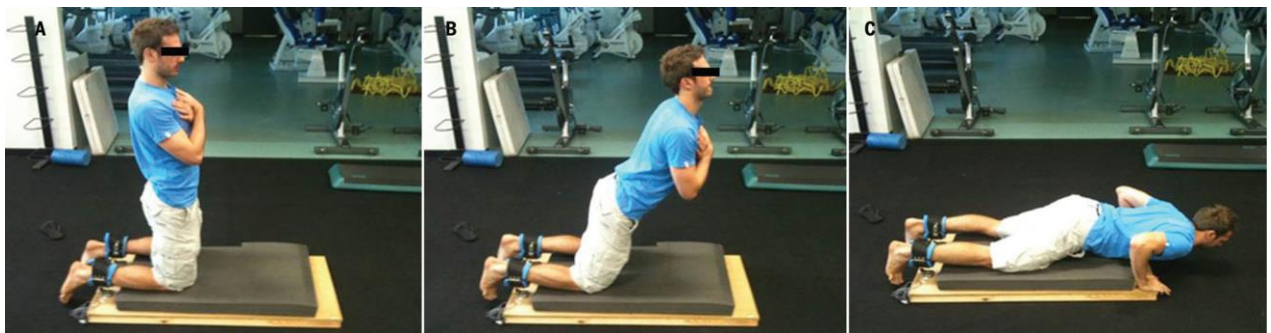


Figure 1: The Nordic hamstring exercise sequence performed during testing on the device (progressing from left to right). After the completion of the exercise (fallen to the ground), participants will slowly return to the starting position by pushing up with both hands (not shown).

You will be familiarised with the testing protocol prior to testing dates.

Your rights during the study

Your participation in the study is entirely voluntary. You are not expected to participate and you may withdraw your consent to participate freely, without prejudice and without any consequence at any time.

Risks associated with participating

There is potential for minor risks during the study as you will be performing maximal testing of the hamstring muscles. Risks may include some muscle soreness for some days after the testing as well as a small potential for muscle tears if movement is not completed properly. Steps have been taken to ensure your safety at all times.

The Hamstring assessment device has been used with many hundreds of athletes from several sporting codes with multiple testing sessions with no reported injuries or adverse effects. The testing sessions you will be involved in will follow the same warm-up and testing protocol as previously performed by Dr David Opar and Dr Tony Shield, the developers of this device.

Benefits of participating in the study

By participating in this study, you will receive valuable information about the strength of each of your hamstring muscles. The information can determine if you have generally weak hamstrings or any strength imbalances between hamstrings that may increase your injury risk. By returning the strength balance between legs it will help to reduce the risk of hamstring strains.

The information collected from participating in the study will help to develop an understanding of the demands on the hamstrings in cricket across all different skills levels ranging from school teams to elite cricket teams and how we may improve these measures of hamstring strength via the use of visual feedback.

Who gets the results?

If you wish to have a copy of your personal results, we are happy to send a report and detailed explanation to you. At the request of the team physiotherapist, strength and conditioning coach and team coach, with your approval, they may receive your results in order to increase the performance of the team.

All results are confidential

All of your personal information and results will be kept completely confidential. Your results will only be viewed by the appropriate researchers. When your results are produced,

no names will be identified in any case. The results will be held on a password protected computer and no information will be disclosed to third parties without your consent.

Questions/further information

If you have any further questions regarding any part of this study, please feel free to contact the chief investigator of the study, Dr Justin Keogh from the Faculty of Health Sciences and Medicine on 5595 4487 or any of the other researchers listed on page 1.

Principle Researcher: Dr Justin Keogh **Signature:** _____

Co-Researcher: Wade Chalker **Signature:** _____

Should you have any complaints concerning the manner in which this research is being conducted, please do not hesitate to contact Bond University Research Ethics Committee:

**Bond University Human Research Ethics Committee,
c/o Bond University Office of Research Services.
Bond University, Gold Coast, 4229**

Tel: +61 7 5595 4194 Fax: +61 7 5595 1120 Email: buhrec@bond.edu.au

Appendix C: Participation Information Form – Study 2

EXPLANATORY STATEMENT

BUHREC Protocol Number: RO1824

STUDY TITLE: Differences in Eccentric Hamstring Strength and Asymmetries Across Elite, Sub-elite and School Level Cricket Players

FACULTY OF HEALTH
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Wade Chalker

Bond University
0425 852 195

Dr Anthony Shield

Queensland University of Technology
07 3138 5829

Dr David Opar

Australian Catholic University
+613 9953 3742

Who is doing the study?

Hamstring strains are becoming a more common injury in sports including cricket. Researchers from Bond University are conducting this study to evaluate the symmetry of hamstring strength in cricket players of different standards and how visual feedback of the hamstring force output may alter your ability to symmetrically produce force with both legs.

The results from the study will be used by the coaching staff and strength and conditioning staff of each team to improve player development.

Why are we doing the study?

We are conducting the following study as there is limited research based on strength in hamstring muscles for cricket players as hamstring strains are amongst the highest occurring injuries in cricket. This research will help to identify asymmetries or deficits in hamstring strength which may lead to an increased risk of hamstring injury and determine if the use of visual feedback of force outputs during the hamstring exercise may reduce these asymmetries and deficits.

Your involvement in the study

If you choose to participate in the study, you will be asked to attend three testing sessions during training for your team. Each session will require ~10 minutes of your time to collect enough data. There will be an explanation session where you will observe a demonstration about the testing protocol, partake in a familiarisation session on the testing device, complete an informed consent document, have any questions that you may have answered and complete some basic measurements such as height and weight. A previous injury report may be required for your team's physiotherapist, medical staff or yourself to complete.

Testing will occur once a week at the start of your team's pre-season training for two consecutive weeks. Each time you perform the test you will perform a standardized warm-up and then perform two maximal sets of three repetitions on the testing device. In total, you will be involved in three sessions over three weeks.

Testing will require you to perform a Nordic hamstring exercise on a device that will measure your force output of both left and right legs. You will be required to perform this test while observing your force outputs in order to assess the effectiveness of real-time feedback on any limb imbalances.

Nordic hamstring exercise testing

During each testing day, you will be required to wear comfortable clothing and footwear appropriate for performing maximal strength testing.

Each testing day will consist of you performing a submaximal warm-up set of three repetitions on the device followed by two sets of three repetitions with 15 seconds rest between repetitions. Each set will be separated by four minutes rest.

The Nordic hamstring exercise will be performed on the testing device seen in Figure 1. Force gauges are attached to your ankle during the movement to measure the force output of each hamstring muscle group.

You will need to perform the Nordic hamstring exercise with the following movement requirements:

- Gradually lean forward at the slowest possible speed
- Maximally resist the forward moving motion with both limbs
- Hold your trunk and hips in a neutral position throughout the manoeuvre
- Keep hands across your chest until you have lost control of movement

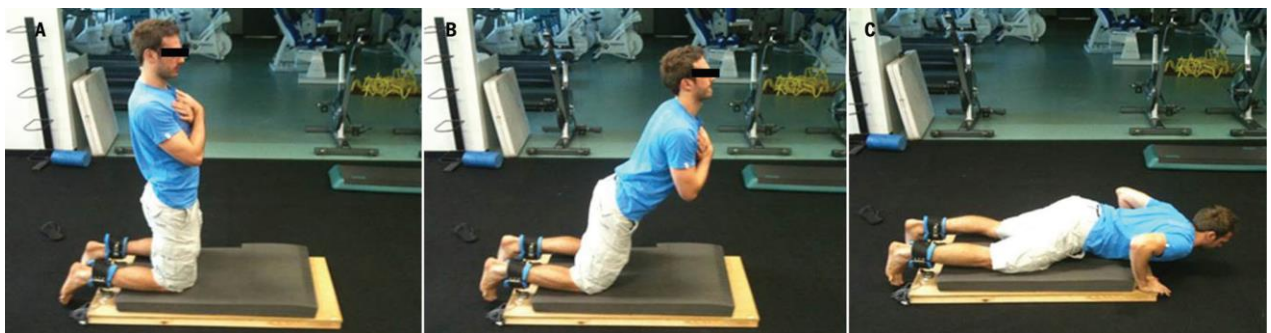


Figure 1: The Nordic hamstring exercise sequence performed during testing on the device (progressing from left to right). After the completion of the exercise (fallen to the ground), participants will slowly return to the starting position by pushing up with both hands (not shown).

You will be familiarised with the testing protocol prior to testing dates.

On alternating weeks, you will perform the Nordic hamstring exercise with a real-time visual feedback of your force outputs. This stage of testing is to assess the ability for you to improve your results while viewing your performance as you complete the movement.

Your rights during the study

Your participation in the study is entirely voluntary. You are not expected to participate and you may withdraw your consent to participate freely, without prejudice and without any consequence at any time.

Risks associated with participating

There is potential for minor risks during the study as you will be performing maximal testing of the hamstring muscles. Risks may include some muscle soreness for some days after the testing as well as a small potential for muscle tears if movement is not completed properly. Steps have been taken to ensure your safety at all times.

The Hamstring assessment device has been used with many hundreds of athletes from several sporting codes with multiple testing sessions with no reported injuries or adverse effects. The testing sessions you will be involved in will follow the same warm-up and testing protocol as previously performed by Dr David Opar and Dr Tony Shield, the developers of this device.

Benefits of participating in the study

By participating in this study, you will receive valuable information about the strength of each of your hamstring muscles. The information can determine if you have generally weak hamstrings or any strength imbalances between hamstrings that may increase your injury risk. By returning the strength balance between legs it will help to reduce the risk of hamstring strains.

The information collected from participating in the study will help to develop an understanding of the demands on the hamstrings in cricket across all different skills levels ranging from school teams to elite cricket teams and how we may improve these measures of hamstring strength via the use of visual feedback.

Who gets the results?

If you wish to have a copy of your personal results, we are happy to send a report and detailed explanation to you. At the request of the team physiotherapist, strength and conditioning coach and team coach, with your approval, they may receive your results in order to increase the performance of the team.

All results are confidential

All of your personal information and results will be kept completely confidential. Your results will only be viewed by the appropriate researchers. When your results are produced, no names will be identified in any case. The results will be held on a password protected computer and no information will be disclosed to third parties without your consent.

Questions/further information

If you have any further questions regarding any part of this study, please feel free to contact the chief investigator of the study, Dr Justin Keogh from the Faculty of Health Sciences and Medicine on 5595 4487 or any of the other researchers listed on page 1.

Principle Researcher: Dr Justin Keogh **Signature:** _____

Co-Researcher: Wade Chalker **Signature:** _____

Should you have any complaints concerning the manner in which this research is being conducted, please do not hesitate to contact Bond University Research Ethics Committee:

**Bond University Human Research Ethics Committee,
c/o Bond University Office of Research Services.
Bond University, Gold Coast, 4229
Tel: +61 7 5595 4194 Fax: +61 7 5595 1120 Email: buhrec@bond.edu.au**

Appendix D: Hamstring Strain Injury Incidence Rates

Author (Year)	Sport	Brief Description	Incidence rates		Prevalence rates	Other Injury Rates
			Overall Injuries	Hamstring Strain Injuries	Hamstring Strain Injuries	
Braham et al. (2004)	Australian football at community level	2001 season - 301 players	12.1/1000 hours			Lower leg 11.8% hamstring/thigh 10.3% Injury rate - 210 injuries for 116 players
Brooks et al. (2006)	Professional rugby union	2002-2004 (two seasons) - 12 English premiership rugby union clubs, 546 players		0.27/1000 player training hours 5.6/1000 player match hours		From 546 players, 22% sustained at least one HSI
Cross et al. (2010)	National Collegiate Athletic Association; soccer and American football			Soccer men 0.691/1000 athlete exposures (aes) - women 0.381/1000 Aes Football men 0.604/1000 Aes		
Frost and Chalmers (2014)	Professional cricket – New Zealand	2002-2008 - 248 elite males	Domestic 27.2/10000 player match hours International 51.6/10000 player match hours		Domestic and international 11.1%	HSIs for international 12%, domestic 9.7%
			Domestic T20 (3 years) -45.8/10000 player match hours			HSIs for pace bowlers 18.7%
			Domestic 1 day (6 years) - 36.2/10000 player match hours			
			Domestic four day (6 years) - 24.1/10000 player match hours			
			International T20 (4 years) - 122.3/10000 player match hours			
			International 1 day (6 years) - 73.1/10000 player match hours			
			International test (6 years) - 30.1/10000 player match hours			
Gabbe et al. (2002)	Australian football at community level	Five amateur teams, one season, 320 participants	27.2/1000 player hours		13.7%	

Leary and White (2000)	Professional cricket - England	1985-1995- 54 cricketers, one team	57.4/1000 days played			
Mansingh et al. (2006)	Professional cricket – West Indies	2003-2004 - 33 international players, 162 domestic players	International test, 48.7/10000 player hours		11.30%	Batsmen and pace bowlers sustained 80% of all injuries
			International 1 day, 40.6/10000 player hours		8.10%	
			Domestic first class, 13.9/10000 player hours			
			Domestic 1 day, 25.4/10000 player hours			
Orchard et al. (2002)	Professional cricket – Australia	1995-2001 seasons (six seasons)	4 day domestic, 17.3/10000 player hours			Overall injury prevalence of HSIs 11%
			1 day domestic, 23.8/10000 player hours		HSIs for pace bowlers 1%	
			First class (total 1 day plus 4 day) domestic, 19/10000 player hours		7%	
			1 day international, 38.1/10000 player hours		10%	
			Test international, 21.4/10000 player hours		HSIs for pace bowlers 13.7%	
			International total, 27.6/10000 player hours			
Orchard et al. (2011)	Professional cricket – Australia	2001-2011 (10 seasons) (Seven for international T20, six for domestic T20)	Domestic T20, 204.5/1000 days of play			Average injury prevalence of HSIs for all teams 10.9%
			Domestic 1 day, 254.1/1000 days of play			HSI Prevalence for pace bowlers for entire study 18.2%
			Domestic 4 day, 117.6/1000 days of play			
			International T20, 214.3/1000 days of play			

			International 1 day, 231.8/1000 days of play			
			International test, 98.3/1000 days of play			
Stretch (2003)	Professional cricket - South Africa	1998-2001 (three seasons) – 436 domestic and international players		No incidence rate reported		
Arnason et al. (2004)	Semi-professional soccer			3/1000 player match hours 0.5/1000 player training hours		

Appendix E: Submitted abstract for the 5th World Congress of Science and Medicine
in Cricket



Eccentric hamstring strength asymmetries and the effect of augmented feedback in elite cricket players: a pilot study

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Aims:

Hamstring strain injuries (HSIs) account for 8-11.1% of all injuries in first class cricket (Frost and Chalmers, 2012). Although HSIs do occur in batsmen and fielders, it is the pace bowlers who are most prone to this injury type (Frost and Chalmers, 2012). Strength asymmetries between limbs have been suggested to increase the risk of HSIs (Opar et al., 2012). This may be a critical factor for HSI incidences in cricket, especially for fast bowlers who place more stress on the front leg during the bowling phase. One possible way to reduce asymmetries in knee flexor strength and therefore potentially rates of HSIs, may be to provide real-time augmented feedback on force outputs during knee flexor strength assessments and resistance training sessions. Therefore, the aims of this pilot study are to (1) gain some preliminary data on elite cricket player's eccentric knee flexor strength and potential between-limb asymmetries, (2) and assess the effect of augmented feedback via real-time visual force outputs during knee flexor strength testing in reducing between-limb force output asymmetries.

Methods:

Eleven elite level cricket players representing a state team were recruited to participate in the study. The study was conducted over an eleven week training period during the start of the pre-season training. Testing was conducted once a week on consecutive weeks. Eccentric hamstring strength was assessed using the device developed by Shield and Opar (2012), which allows real-time force outputs to be recorded during a Nordic hamstring exercise (NHE). Participants all completed a standardized warm-up followed by one maximal

set of three repetitions of the NHE. Opar et al. (2013) recently reported that this protocol provides a reliable measure for eccentric knee flexor strength. A cross-over design study was used with half of the participants receiving augmented visual feedback of their force outputs in the first four weeks of training and the second half receiving augmented feedback in the second four week block of training. A pre, mid and post intervention test was conducted at weeks one, six and eleven to assess the chronic effect of augmented feedback on knee flexor force output.

Results:

The mean eccentric hamstring force output was recorded at the start of pre-season training for the entire group ($n = 20$, $289.97\text{N} \pm 58.8$ and $323.56\text{N} \pm 70.3$ for left and right respectively), and compared between the bowlers ($n=12$, $294\text{N} \pm 61.8$ and $329.8\text{N} \pm 63.4$ for left and right respectively) and the batters ($n = 8$, $284\text{N} \pm 57.6$ and $314.3\text{N} \pm 83.3$ for left and right respectively). There was a 9.8% eccentric hamstring strength imbalance across the entire group. The AF group ($n = 7$) had a significant increase in force output for both mid and post measures when compared to pre-intervention measures ($P < 0.05$), while no significant effect was seen for the NF group ($n = 2$). While non-significant, possible trends for reductions in limb asymmetry for the AF group were observed with augmented feedback from pre (7.1%) to mid (3.1%), with this maintained when feedback was removed to the post-intervention (3.9%) tests. Small changes were observed for the NF group from pre (7.6%) to mid (6.2%) and post-intervention (3%) tests.

Discussion and Conclusions:

It was hypothesized that using real-time visual feedback of force outputs during the NHE would reduce between-limb asymmetries compared to no feedback. If this approach is successful in reducing between-limb knee flexor strength asymmetries during the NHE, it is proposed that it will help to reduce the risk of sustaining a HSI during match play and training. Moreover, with further knowledge of the effect of playing positions on eccentric hamstring strength, appropriate training approaches may be applied to help reduce the risk of future HSIs.

References:

- FROST, W. L. & CHALMERS, D. J. 2012. Injury in elite New Zealand cricketers 2002–2008: descriptive epidemiology. *British Journal of Sports Medicine*.
- OPAR, D. A., WILLIAMS, M. D. & SHIELD, A. J. 2012. Hamstring strain injuries: factors that lead to injury and re-injury. *Sports Med*, 42, 209-26.
- SHIELD, A. J. & OPAR, D. A. 2012. Eccentric Hamstring Strength Testing Device. International Patent PCT/AU2012/001041.2012

OPAR, D. A., PIATKOWSKI, T., WILLIAMS, M. D. & SHIELD, A. J. 2013. A Novel Device Using the Nordic Hamstring Exercise to Assess Eccentric Knee Flexors Strength: A Reliability and Retrospective Injury Study. J Orthop Sports Phys Ther.

Appendix F: Submitted abstract for the 5th World Congress of Science and Medicine
in Cricket



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A review of hamstring strain injuries in cricket and potential methods to reduce the high occurrence of strains

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Aims:

Cricket was once regarded as a “moderate injury risk” sport. However, more recent statistics suggests that the injury rate in elite cricket is rising, with hamstring strain injuries one of the most common and severe injuries (Frost and Chalmers, 2014). Therefore, the aims of the present study are to (1) review the literature surrounding cricket injuries, especially those to the hamstrings and (2) highlight hamstring injury prevention protocols used in other sports that may reduce the incidence and/or severity of hamstring strains in cricket.

Methods:

The literature reviewed in this paper was sourced using SPORTDiscus, Pubmed and Embase databases. Key words included; cricket, hamstrings, strains, injuries, prevention and Nordic hamstring exercises. Articles were searched from 1969-2014, obtaining full text articles. Articles that matched key words in the abstract were included for review. Further articles were sourced after review of article reference lists if the articles were relevant to the key words. From the abstract review, articles were included if they related to cricket injuries, hamstring strains, causation, treatment or prevention.

Discussion and Conclusions:

Multiple cricket playing nations have documented the occurrence of cricket injuries over several seasons and all have demonstrated an increase in injuries over recent times with the introduction of Twenty20 cricket and the increase in matches played per year (Frost and Chalmers, 2014, Orchard et al., 2011). International cricket injury reports suggest that pace

bowlers are most at risk of incurring an injury (Frost and Chalmers, 2014, Orchard et al., 2011). Hamstring strain injuries (HSIs) in cricket account for 8-11.1% of all injuries (Frost and Chalmers, 2014, Orchard et al., 2011). This appears similar to Australian Rules Football (HSI occurrence rate of 7-14%) (Hrysomallis, 2013), suggesting that HSIs are just as common in cricket as they are in other high intensity sports. Little is known as to what predisposes cricket players to HSIs but other sporting models suggest that risk factors can be; hamstring muscle weakness, increasing age, previous hamstring injury, lack of hamstring flexibility, poor lumbar posture, muscle fatigue and biomechanical abnormalities. Hamstring strength imbalances can be of particular problem for cricket players, in particular, pace bowlers due to the asymmetrical demands of fast bowling and throwing. Addressing strength imbalances and improving eccentric hamstring strength have been proposed as a key component of HSI prevention. The Nordic hamstring exercise in particular could provide cricket players a feasible and effective way to reduce the risk of sustaining a HSI and reducing the number of HSIs occurring in cricket throughout the world. Shield and Opar (2012) have recently developed and validated a hamstring testing device for the assessment of eccentric hamstring strength and between-leg asymmetries. We would therefore recommend that elite cricket players adapt training models from other sports that target HSI risk factors so to reduce the risk as much as possible and employ regular eccentric hamstring training and assessment, easily performed using the device developed by Shield and Opar (2012).

References:

- FROST, W. L. & CHALMERS, D. J. 2014. Injury in elite New Zealand cricketers 2002-2008: descriptive epidemiology. *Br J Sports Med*, 48, 1002-7.
- ORCHARD, J., JAMES, T., KOUNTOURIS, A., BLANCH, P., SIMS, K. & ORCHARD, J. 2011. Injury Report 2011: Cricket Australia. *Sport Health*, 29, 16-29.
- HRYSOMALLIS, C. 2013. Injury Incidence, Risk Factors and Prevention in Australian Rules Football. *Sports Medicine*, 43, 339-354.
- SHIELD, A. J. & OPAR, D. A. 2012. Eccentric Hamstring Strength Testing Device. International Patent PCT/AU2012/001041.2012